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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

DTNSRDC/SPD 1035-01

AD A114915

DETERMINATION OF DRAG COEFFICIENTS
FOR A BUOYANT-CABLE ANTENNA

by

Alan M. Israel

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SHIP PERFORMANCE DEPARTMENT
DEPARTMENTAL REPORT

March 1982

DTNSRDC/SPD 1035-01

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NDW-DTNSRDC 5602/30 (2-80)
(supersedes 3960/46)

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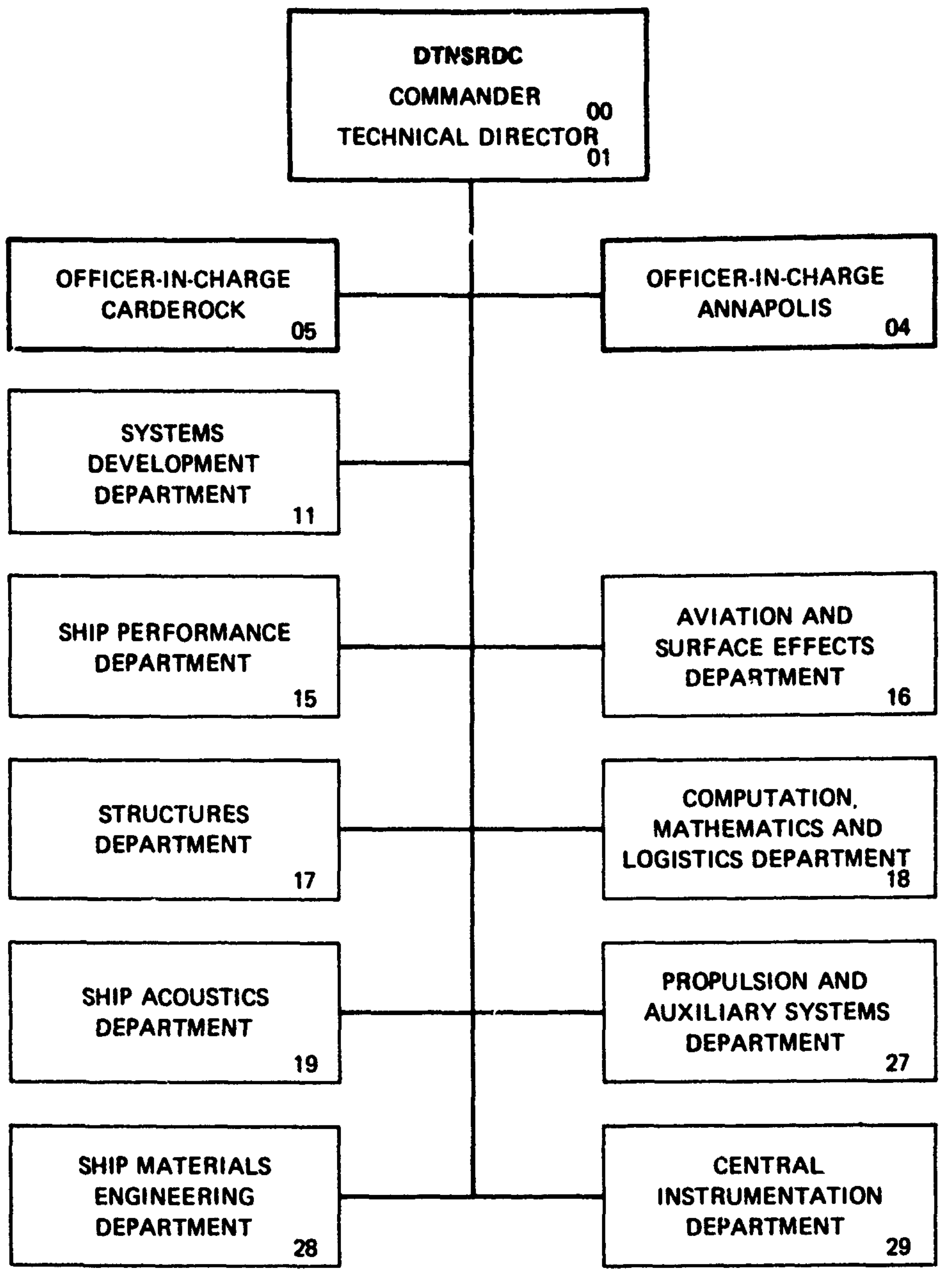
MAJOR DTNSRDC ORGANIZATIONAL COMPONENTS



GPO 866 993
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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DTNSRDC/SPD 1035-01	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DETERMINATION OF DRAG COEFFICIENTS FOR A BUOYANT-CABLE ANTENNA		5. TYPE OF REPORT & PERIOD COVERED Departmental
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Alan M. Israel		8. CONTRACT OR GRANT NUMBER(s) Contract No. N00030-79-C-0091 DTNSRDC W. U. 1-1548-043
9. PERFORMING ORGANIZATION NAME AND ADDRESS David Taylor Naval Ship R&D Center Ship Performance Department Bethesda, Maryland 20084		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Sperry Systems Management Great Neck, New York 11020		12. REPORT DATE March 1982
		13. NUMBER OF PAGES 44
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Buoyant cable
Cable antennas
Cable hydrodynamics
Tangential cable measurements
Drag evaluation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Samples of buoyant cable antennas of various lengths and surface roughnesses were towed over a range of speeds and depths in different wave conditions. Based on measurements of the forces developed and using computerized prediction techniques, normal and tangential drag coefficients were determined for the submerged segment of the BCA configuration and drag coefficients

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NOTATION

A	Wave Amplitude
C_f	Floating Length Drag Coefficient $\left(\frac{D_f}{\frac{1}{2}\rho V^2\ dS}\right)$
C_R	Submerged Segment Normal Drag Coefficient $\left(\frac{F}{\frac{1}{2}\rho V^2 d}\right)$
Cw	Wetted Circumference
D_f	Drag of the Floating Length
d	Diameter
F	Normal Component of Hydrodynamic Force per Unit Length
f	Form Factor (G/R)
G	Tangential Component of Hydrodynamic Force per Unit Length
Rn	Reynolds Number (Vd/ν)
S	Scope or Length
S_f	Length of the Floating Segment
T	Wave Period
V	Velocity
V_K	Velocity in knots
Δ	Change in a given parameter
δ	Variation of a function due to variation in the independent parameters
ν	Kinematic Visocity
ρ	Density
σ	Standard Deviation
ϕ	Angle of the Buoyant Cable Antenna relative to horizontal
∂	Partial Derivative

ABSTRACT

Sample of buoyant cable antennas of various lengths and surface roughnesses were towed over a range of speeds and depths in different wave conditions. Based on measurements of the forces developed and using computerized prediction techniques, normal and tangential drag coefficients were determined for the submerged segment of the BCA configuration and drag coefficients were determined for the floating length segment. The drag coefficients are presented in both tabular and graphical form.

The results indicate that both waves and surface roughness can have a significant effect on the drag coefficients. The results also indicate that the effects of cable stiffness on the accuracy of the cable catenary predictions require further investigation.

ADMINISTRATIVE INFORMATION

The research and development program described in this report was funded by Sperry Systems Management under Navy Contract No. N00030-79-C-0091 (Sperry Systems Management Purchase Order P-183-767) of 26 October 1978, David Taylor Naval Ship Research and Development Center Work Unit 1-1548-043.

INTRODUCTION

The ability to predict accurately the catenary of a buoyant cable antenna (BCA) towed from either a submarine or a submarine communications buoy is critical for accurate navigation. The accuracy of the predictions is directly related to the determination of the hydrodynamic drag coefficients representative of BCAs. Prompted by a history of poor correlation between predicted and measured BCA catenaries, the David Taylor Naval Ship Research and Development Center (DTNSRDC) was requested by Sperry Systems Management (SSM) to conduct basin experiments to determine the drag coefficients of BCAs. The effects of surface waves and cable surface roughness on the drag coefficients also were to be determined experimentally.

In these experiments, various length samples of BCA were towed over a range of speeds and depths in calm water and in waves. A computer program was used to determine the BCA drag coefficients based on the measured hydrodynamic forces developed by the BCA.

In this report, normal and tangential drag coefficients for the submerged segment and drag coefficients for the floating length segment of the BCA are tabulated and plotted as functions of Reynolds Number for various wave conditions. The definition and development of the equations for the drag coefficients also are presented.

MODEL DESCRIPTION

The BCA samples evaluated are designated RG-384/U and are typical of the type of BCA currently used on submarines. A cross-section of the antenna cable is shown in Figure 1. Two lengths of RG-384/U that had been used aboard submarines were supplied for this evaluation. These lengths differed in surface roughness and in a series of indentations in the surface material. The difference in indentations was due to the variation in pay-out mechanisms between different submarines.

When the BCA samples were received at DTNSRDC, they were wound tightly on small diameter spools. Due to the nature of the BCA jacket material, a "memory" or hysteresis in the samples gave them a tendency to curl into a helix. In an attempt to reduce the effect of this memory, the samples were stretched in the sun under tension for approximately 2 weeks prior to the evaluation. Even after 2 weeks, the samples still had a tendency to curl, although the effect had been considerably reduced.

The two samples of BCA are referred to as Sample 1 (which had the rougher surface) and Sample 2. Sample 1 was first cut into a 400-foot (122-m) length, referred to as Sample 400-1, and a 100-ft (30-m) length, referred to as Sample 100-1. A 200-ft (61-m) length, subsequently cut from Sample 400-1, is referred to as Sample 200-1. Sample 2 was cut to form a 100-ft (30-m) length, referred to as Sample 100-2.

Each BCA was marked along its entire length with bands of colored tape spaced 2 ft (0.6 m) apart for the first 100 ft (30 m) of the cable and 10 ft (3 m) apart for the remaining length of the cable.

The diameter of each length to be evaluated was measured with a micrometer every 2 ft (0.6 m) along the antenna. At each station, two measurements were taken 90 degrees apart to account for any out-of-roundness. Based on an average diameter at each station, average diameters for each length were calculated and are listed in Table 1. The buoyancy of each sample in fresh water was measured and the specific gravity of each sample determined. The values are also listed in Table 1.

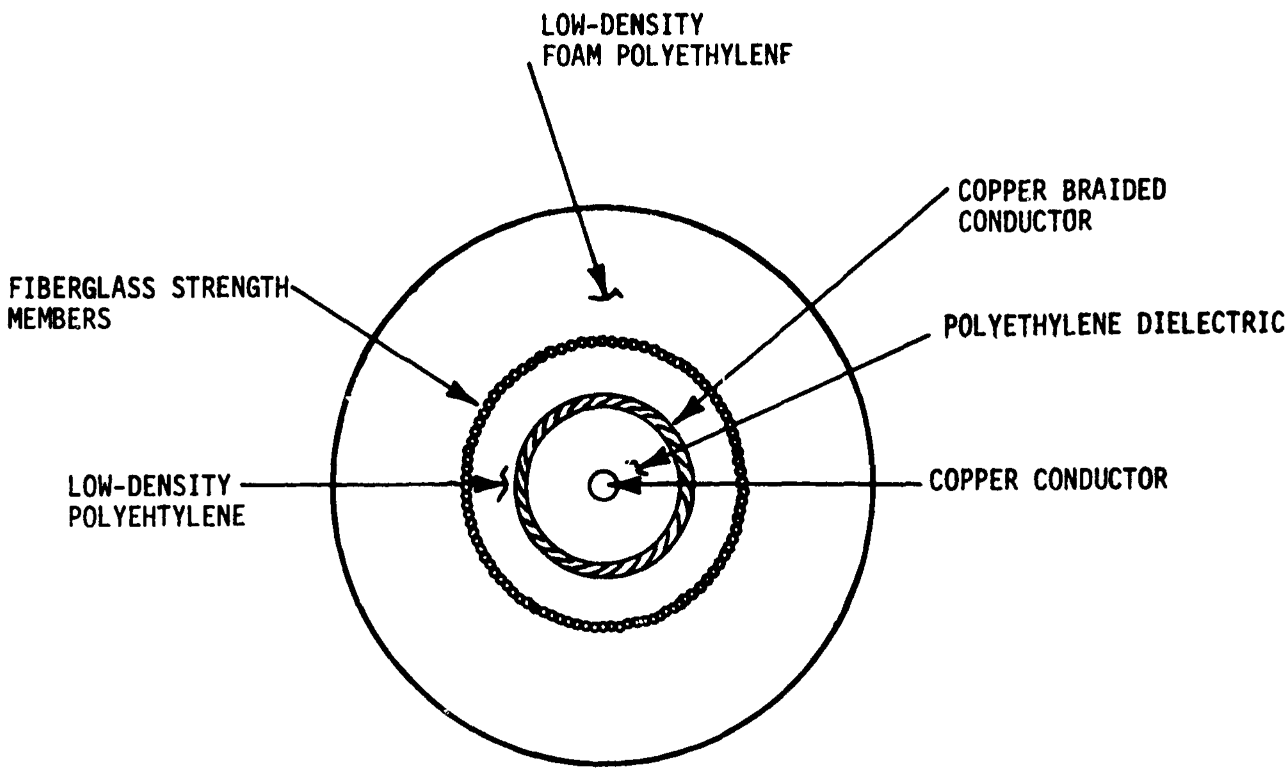

Figure 1 - Buoyant Cable Antenna Composition (Cross-Section)

TABLE 1 - PHYSICAL PROPERTIES OF BCA SAMPLES

Sample	Length ft (m)	Diameter in. (mm)	Buoyancy lb/ft (N/m)	Specific Gravity	Wetted Circumference in. (mm)
100-1	99.75 (30.40)	0.649 (16.48)	0.030 (0.437)	0.80	1.36 (34.54)
200-1	200.04 (60.97)	0.655 (16.64)	0.029 (0.423)	0.80	1.37 (34.79)
400-1	400.04 (121.93)	0.653 (16.58)	0.029 (0.423)	0.80	1.36 (34.54)
100-2	100.04 (30.49)	0.643 (16.33)	0.029 (0.423)	0.80	1.33 (33.78)

Note: The buoyancies were measured in fresh water with a density of 1.9362 slug/ft^3 (997.72 kg/m^3).

The wetted circumference Cw of a BCA is defined as the circumferential length in contact with the water when a BCA sample is allowed to float at zero speed in calm water. Both cable diameter and specific gravity affect the value of Cw. Based on a hydrostatic force balance, the value of Cw for each sample was determined and is presented in Table 1.

EXPERIMENTAL APPARATUS AND INSTRUMENTATION

The BCA samples were evaluated in the high-speed basin at the David Taylor Naval Ship R&D Center. The basin is 16 ft (4.8 m) deep, 21 ft (6.4 m) wide and 2968 ft (904.6 m) long and is filled with fresh water at a temperature of 70°F (21°C). The towing arrangement is shown in Figure 2. A faired strut attached to vertical rails on the carriage provided a submerged towpoint which allowed variations in towpoint depths ranging from 0 to 5 ft (2 m). A tape measure attached to the side of the strut indicated towpoint depth. Strain-gaged ring dynamometers attached to a spreader plate at the bottom of the strut provided measurement of BCA towing tension. Since the accuracy of the drag coefficient calculations is strongly dependent on the accuracy of the tension measurements, the use of highly accurate transducers was necessary. Therefore, a 50-lb (225-N) capacity dynamometer was used

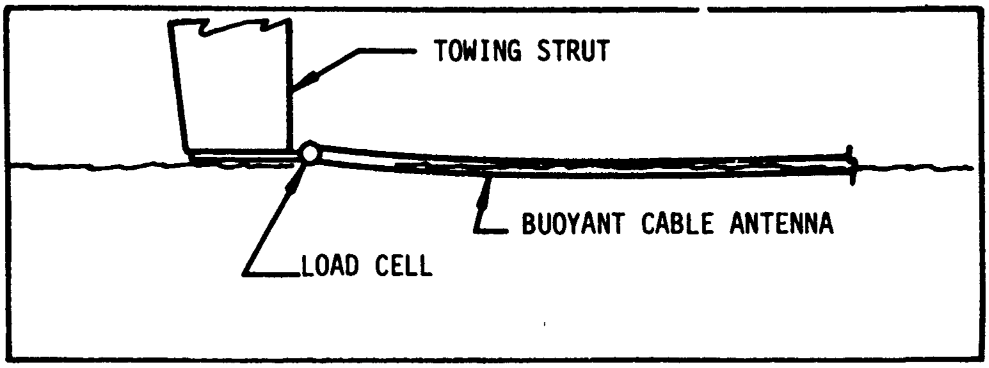

Figure 2a - Towing Arrangement for Surface Tows

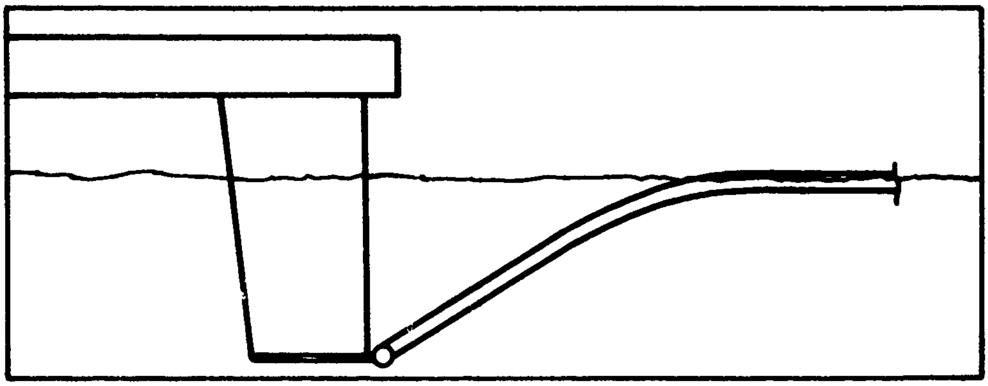

Figure 2b - Towing Arrangement for Hybrid Tows

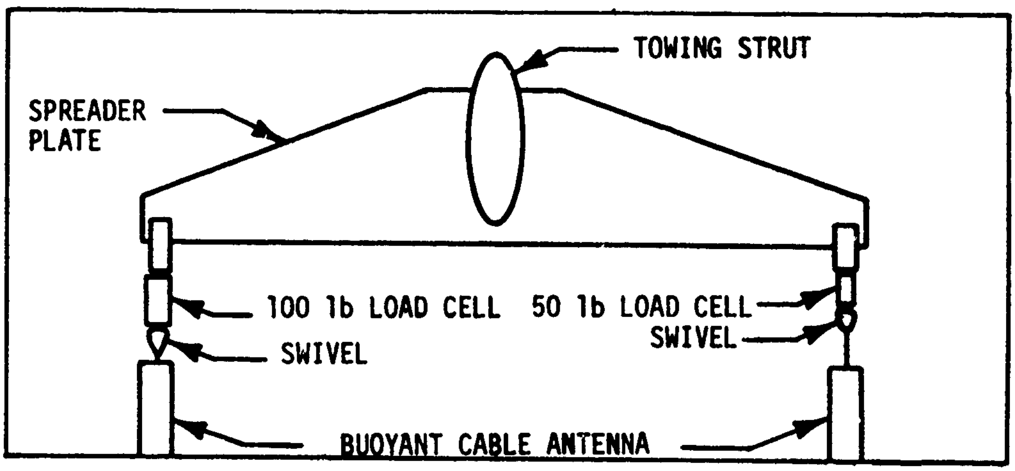

Figure 2c - BCA Attachment Plate

Figure 2 - Towing Configurations in High-Speed Basin

for the 100-ft (30-m) samples and a 100-lb (450-N) capacity dynamometer was used for the 400-ft (122-m) sample at speeds of 8 knots (5 m/s) and above. As shown in Figure 2c, the dynamometers were located 9.5 in. (241 mm) to either side of the towing strut to minimize the effects of the strut wake on the motion of the BCA. The towing velocity was measured by a magnetic pick-up attached to the towing carriage, and a sonic probe was utilized for measurements of wave height. All transducers and their associated accuracies are presented in Table 2.

EXPERIMENTAL PROCEDURES

The evaluation was divided into two parts. The first part consisted of towing the BCA samples in calm water. This part was divided further into surface tows and hybrid tows (a configuration in which the BCA is partially submerged, partially surfaced). The second part consisted of towing the BCA samples in waves and also entailed both surface and hybrid modes of operation.

The BCAs were evaluated in two wave conditions. The first was somewhat irregular and had a wave period of approximately 1.4 sec and an average amplitude of 2.41 in. (61 mm). This wave form is referred to as wave 1. The second was regular and had a wave period of 2.4 s and an average amplitude of 3.0 in. (76 mm). This wave form is referred to as wave 2. These wave forms are shown in Figure 3. The experimental conditions evaluated are listed in Table 3.

SURFACE TOWS/CALM WATER

To determine the drag developed by the floating section of BCA, various samples of BCA were towed on the water surface. The towpoint was positioned 0.5 in. (13 mm) above the water surface, and the tension at the towpoint was measured over the speed range from 3 to 10 knots (1.5 to 5.1 m/s) in 1-knot (0.5-m/s) increments. Samples 100-1, 200-1, 400-1 and 100-2 were evaluated over the entire speed range. At the desired speed, measurements were taken after the carriage had traveled a distance of at least two cable lengths to allow the cable to reach steady-state conditions.

HYBRID TOWS IN CALM WATER

Samples 100-1, 400-1 and 100-2 were towed from towpoint depths of 3.0 ft (0.9 m) and 5.0 ft (1.5 m) at speeds from 3 knots (1.5 m/s) up to the maximum speed at which there was still some length of BCA on the surface. At each speed, tension

TABLE 2 - MEASURED PARAMETERS AND ACCURACIES

Measurement	Transducer	Value and Accuracy
Towspeed	Magnetic Pick-up	3-10 knot ± 0.03 knot (1.5-5.1 m/s ± 0.01 m/s)
Strut Depth	Tape Measure	0,3,5 ft ± 0.005 ft (0, 0.9, 1.5 m ± 0.001 m)
Antenna Diameter	Micrometer	value ± 0.001 in. (0.025 mm)
Antenna Length	Tape Measure	99.75 ft ± 0.02 ft (Sample 100-1) (30.40 m ± 0.006 m) 200.02 ft ± 0.04 ft (Sample 200-1) (60.96 m ± 0.012 m) 400.02 ft ± 0.08 ft (Sample 400-1) (121.92 m ± 0.024 m) 100.02 ft ± 0.02 ft (Sample 100-2) (30.48 m ± 0.006 m)
Antenna Buoyancy	Gram Balance	±0.001 lb/ft (±0.146 N/M)
Water Density	Gram Balance	1.9362 slug/ft^3 ± 0.019 slug/ft^3 (997.7 kg/m^3 ± 9.79 kg/m^3)
Towpoint Tension (Submerged Tows)	Ring-Gage Dynamometer	For the 100 and 200 ft (30.5 and 60.9 m) cables: ±0.25 lb (±1.11 N) For the 400 ft (121.9 m) cable: ±0.25 lb (±1.11 N) at V ≤ 8 knot (4.1 m/s) ±0.50 lb (±2.22 N) at V > 8 knot (4.1 m/s)
Floating Length	Movies of Colored Bands	±0.02 ft (±0.006 m)
Towpoint Tension (Surface Tows)	Ring-Gage Dynamometer	Measured value ±0.25 lb (±1.11 N)
Wave Height	Sonic Probe	Measured value ±0.05 in. (±1.4 mm)

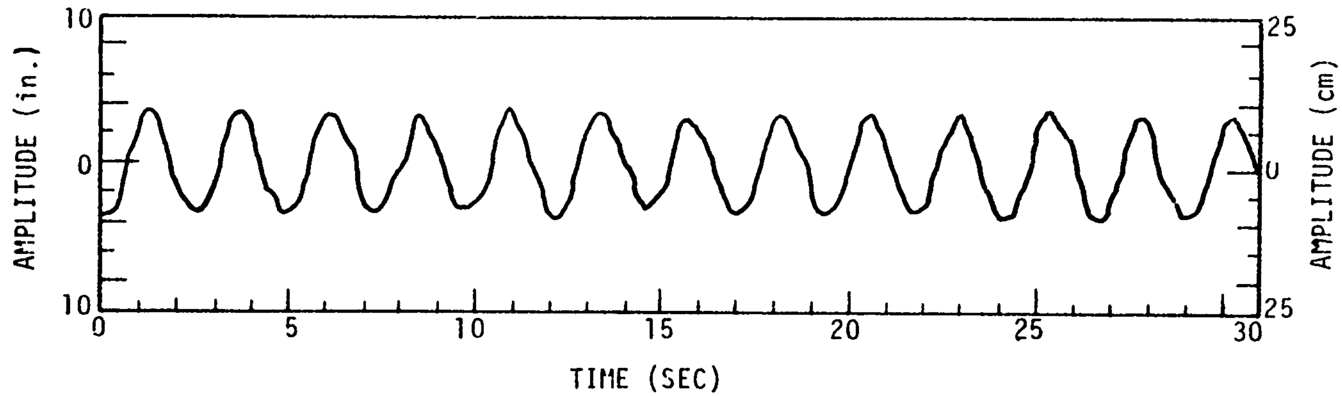

Figure 3a - Wave 2

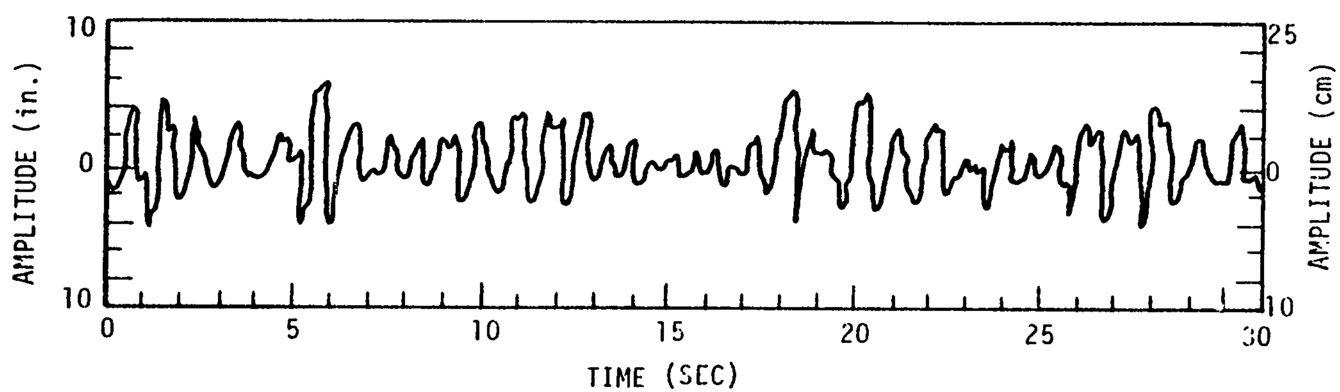

Figure 3b - Wave 1

Figure 3 - Waveforms of Modelled Waves 1 and 2

TABLE 3 - EXPERIMENTAL CONFIGURATIONS

Test No.	Run No.	Sample No.	Wave Period sec	Average Amplitude in.	mm	Strut Depth ft	(m)	Speed Range knots	m/s
1	1-4	100-1	--	--	--	0.0	(0.0)	3.0 - 10.0	(1.5 - 5.1
2	5-11	100-1	--	--	--	3.0	(0.9)	3.0 - 8.0	(1.5 - 4.1)
3	12-16	100-1	--	--	--	5.0	(1.5)	3.0 - 7.0	(1.5 - 3.6)
4	17-19	400-1	--	--	--	0.0	(0.0)	3.0 - 8.0	(1.5 - 4.1)
5	20-25	400-1	--	--	--	3.0	(0.9)	3.0 - 8.0	(1.5 - 4.1)
6	26-31	400-1	--	--	--	5.0	(1.5)	3.0 - 8.0	(1.5 - 4.1)
7	32-33	400-1	--	--	--	0.0	(0.0)	8.0 - 10.0	(4.1 - 5.1)
8	34-35	400-1	--	--	--	3.0	(0.9)	9.0 - 10.0	(4.6 - 5.1)
9	36-37	400-1	--	--	--	5.0	(1.5)	9.0 - 10.0	(4.6 - 5.1)
10	38-40	400-1	1.40	2.17	(55.1)	0.0	(0.0)	7.0 - 10.0	(3.6 - 5.1)
11	41-42	400-1	2.43	3.01	(76.4)	0.0	(0.0)	7.0 - 10.0	(3.6 - 5.1)
12	43-46	400-1	2.43	3.01	(76.4)	5.0	(1.5)	7.0 - 10.0	(3.6 - 5.1)
13	47-50	400-1	1.40	2.17	(55.2)	5.0	(1.5)	7.0 - 10.0	(3.6 - 5.1)
14	51-53	400-1	1.40	2.17	(55.2)	0.0	(1.5)	3.0 - 6.0	(1.5 - 3.1)
15	54-57	400-1	1.40	2.17	(55.2)	5.0	(1.5)	3.0 - 6.0	(1.5 - 3.1)
16	58-59	400-1	2.43	3.01	(76.4)	0.0	(0.0)	3.0 - 6.0	(1.5 - 3.1)
17	60-62	400-1	2.43	3.01	(76.4)	5.0	(1.5)	3.0 - 6.0	(1.5 - 3.1)
18	65-67	200-1	2.43	3.01	(76.4)	0.0	(0.0)	3.0 - 10.0	(1.5 - 5.1)
19	68-69	200-1	1.40	2.17	(55.1)	0.0	(0.0)	3.0 - 10.0	(1.5 - 5.1)
20	70-71	200-1	--	--	--	0.0	(0.0)	3.0 - 10.0	(1.5 - 5.1)
21	89-90	100-1	2.43	3.01	(76.4)	0.0	(0.0)	3.0 - 10.0	(1.5 - 5.1)
22	87-88	100-1	1.40	2.17	(55.1)	0.0	(0.0)	3.0 - 10.0	(1.5 - 5.1)
23	82-86	100-1	1.40	2.17	(55.1)	5.0	(1.5)	3.0 - 10.0	(1.5 - 5.1)
24	95-99	100-1	2.43	3.01	(76.4)	5.0	(1.5)	3.0 - 10.0	(1.5 - 5.1)
25	100-105	100-1	1.40	2.17	(55.1)	5.0	(1.5)	3.0 - 7.0	(1.5 - 3.6)
26	106-108	100-1	1.40	2.17	(55.1)	3.0	(0.9)	3.0 - 7.0	(1.5 - 3.6)
27	72-73	100-2	--	--	--	0.0	(0.0)	3.0 - 10.0	(1.5 - 5.1)
28	74-78	100-2	--	--	--	5.0	(1.5)	3.0 - 7.0	(1.5 - 3.6)
29	79-80	100-2	1.40	2.17	(55.1)	0.0	(0.0)	3.0 - 10.0	(1.5 - 5.1)
30	81	100-2	1.40	2.17	(55.1)	5.0	(1.5)	3.0 - 7.0	(1.5 - 3.6)

at the towpoint and towing velocity were measured. In addition, a movie camera positioned at the side of the towing basin filmed the section of BCA near and at the water surface for the purpose of determining the BCA floating length.

SURFACE TOWS IN WAVES

The procedure used while towing in waves was similar to the procedure used in calm water. Each sample was towed in both waves 1 and 2. At each speed, the towing tension and wave height were measured. The towpoint was positioned at the same height used for calm water, which was 0.5 in. (13 mm) above the mean water surface.

HYBRID TOWS IN WAVES

For purposes of comparison, the samples were towed in wave 1 and 2 at the same speeds and depths used in the calm water hybrid tows. Towing tension and wave height were measured, and movies were taken of the section of BCA near and on the water surface to determine BCA floating length.

EXPERIMENTAL RESULTS AND DISCUSSION

The assumptions and methods used to determine the drag coefficients for the floating lengths are explained in the following section.

SURFACE TOWS

For surface tows, as noted previously, the towpoint is 0.5 in. (1.27 cm) above the water surface, and thus a short length of the cable (approximately 1% to 2% of the total length) is suspended out of the water. The tension measurement, therefore, includes a cable weight component which is very small relative to the drag force. In these measurements the drag is assumed to be equal to the tension.

The tabulated results of the surface-towing experiments for both calm water and waves are presented in Appendix A. The data are plotted logarithmically in Figure 4 to illustrate the dependence of tension on a fixed power of velocity. This power is approximately 2 but varies ±10 percent, depending on the condition of the water surface and on sample length. The values of surface drag (i.e., tension) and velocity are average values for each speed based on five data samples per second.

In all cases, the drag in wave 1 is highest, and the drag in calm water is lowest. A possible explanation for this phenomenon may be seen in Figure 3 showing the waveforms for the two waves. Although the average amplitude of wave 2 is

Figure 4 - Tension in the Floating Length as a Function of Velocity for BCA Samples in Various Wave Conditions

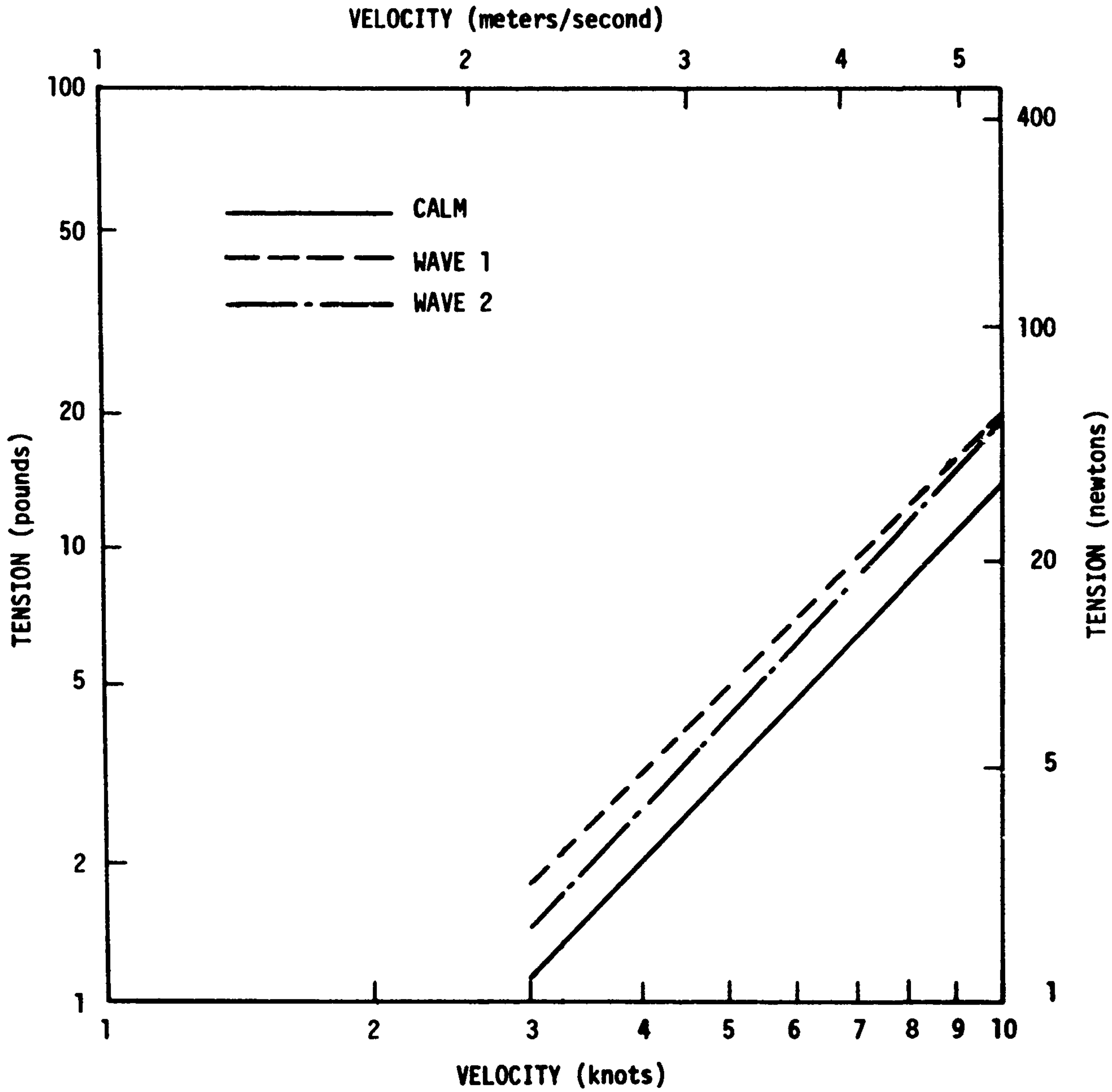

Figure 4a - Sample 100-1

Figure 4 (Continued)

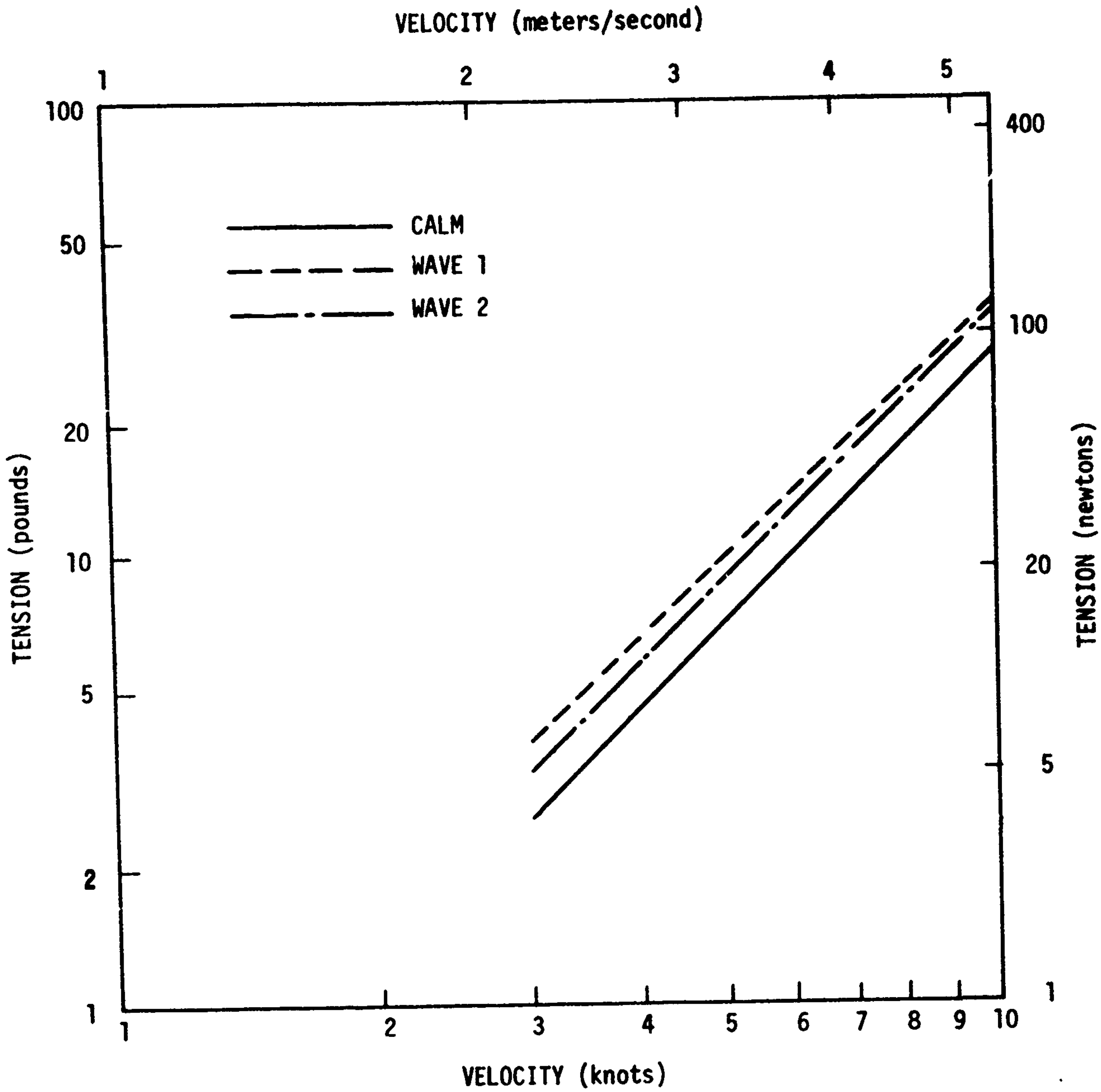

Figure 4b - Sample 200-1

Figure 4 - (Continued)

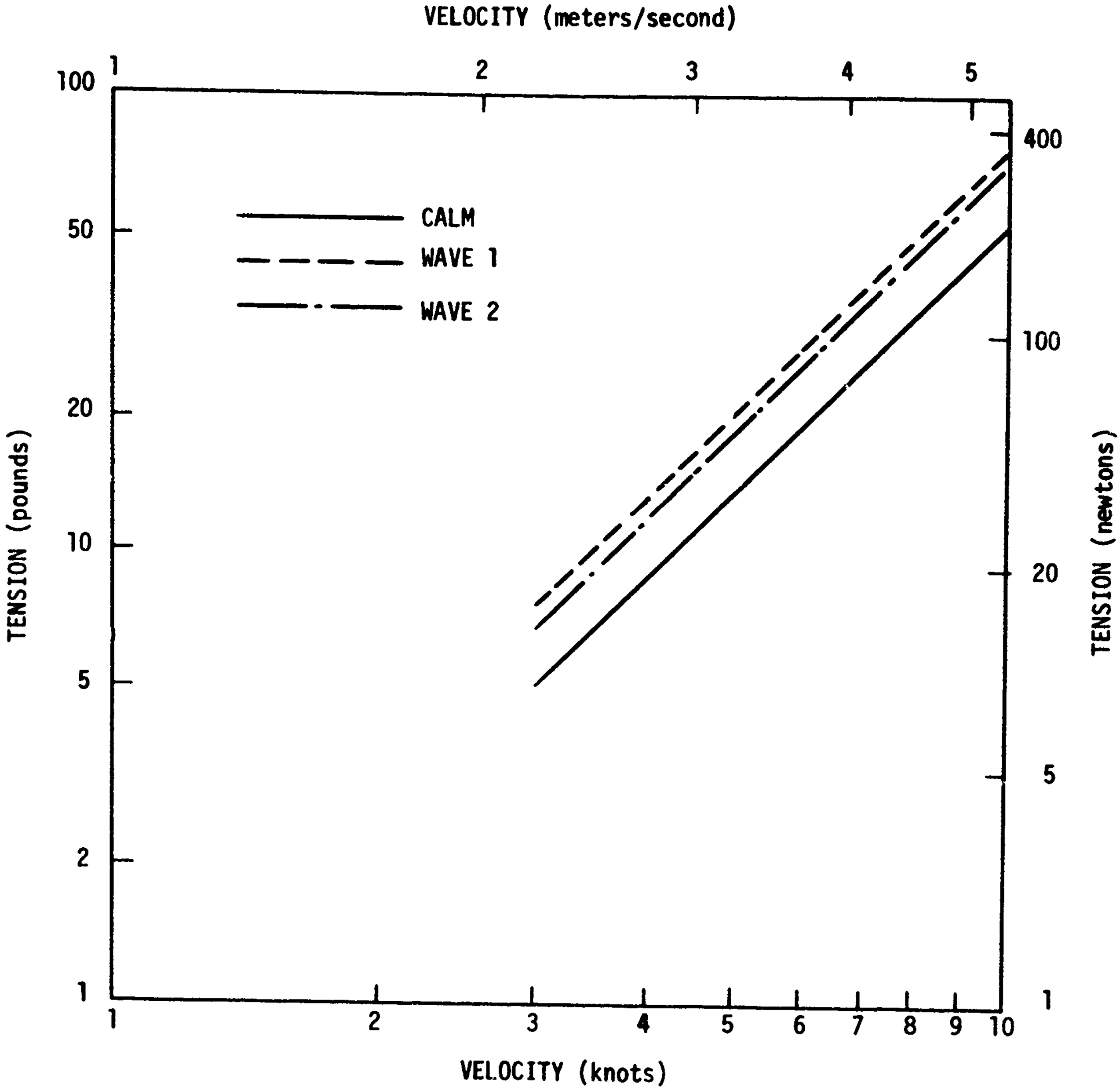

Figure 4c - Sample 400-1

Figure 4 (Continued)

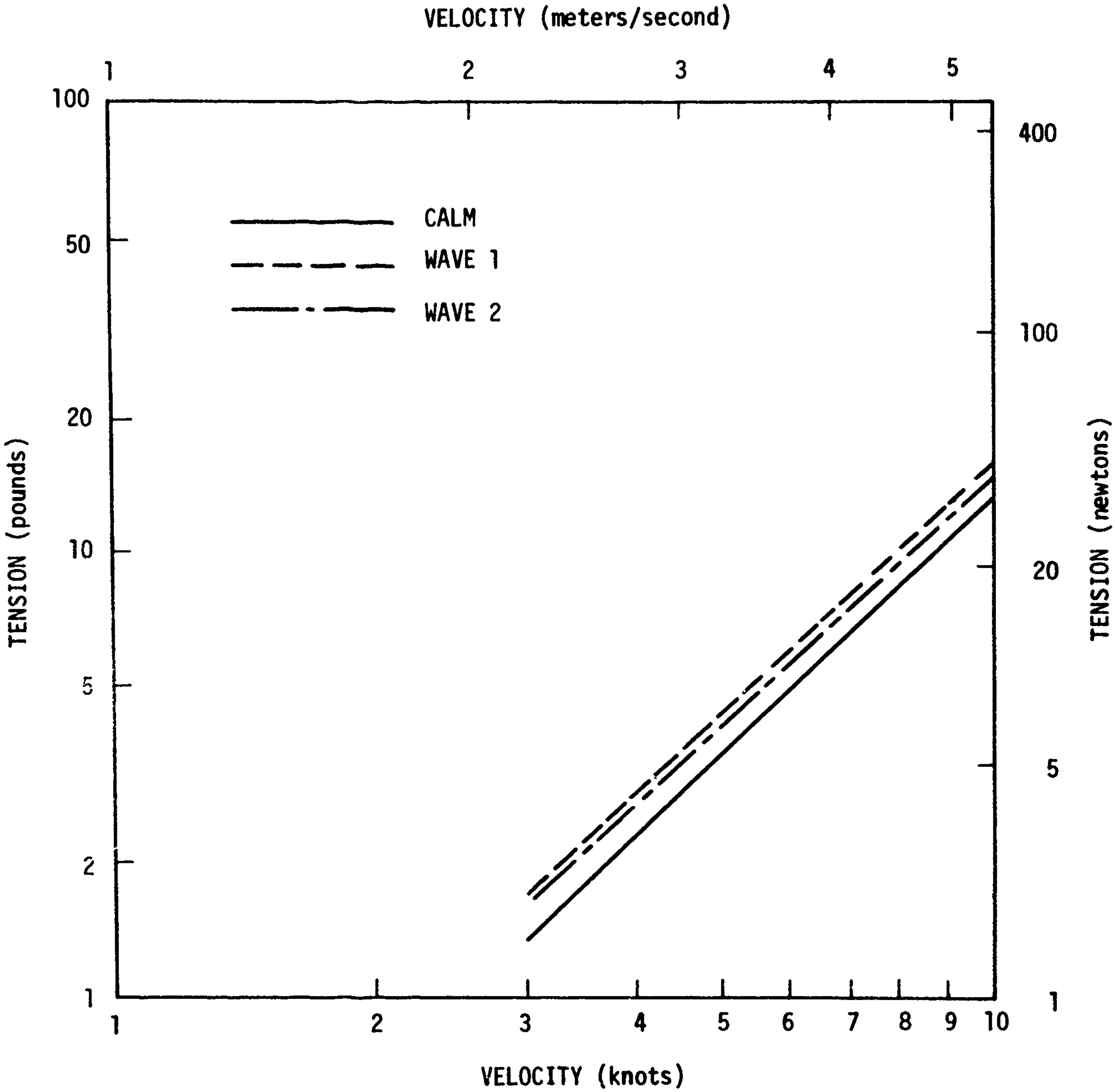

Figure 4d - Sample 100-2

slightly higher than that of wave 1, the latter's waveform is much more regular. Therefore, in wave 1, the BCA would be subjected to much more irregular motions. This may result in a continuous series of small amplitude surges, producing a series of peak tensions considerably higher than would be produced by a smooth sinusoidal waveform.

The effect of cable roughness on drag is seen in Figure 5. Equal lengths of samples 1 and 2 were towed in various sea states. The surface roughness varies considerably between the two samples. In calm water, the surface drag is almost identical for both samples. However, in the presence of waves, surface roughness has a considerable effect, with the rougher surface (Sample 1) having the higher drag. Since the distribution of roughened areas on each sample was so random, it was impossible to quantify the overall surface roughnesses.

During the surface towing, the towpoint was positioned 0.5 in. (12 mm) above the mean water surface to reduce wake effects due to the towing strut. This caused some length of cable to be out of the water. The length out of the water was estimated by observing the colored tape bands used to mark the BCA samples, and is listed in Table A.2 in Appendix A. These lengths are used in the determination of the surface drag coefficient. During surface towing in waves, the towpoint and the first several feet of BCA would occasionally be submerged. At that moment, the submerged length would be larger than the length in Table A.2. However, it was assumed that over a long period of time, the average submerged length in waves was equal to the submerged length in calm water at the same velocity.

The drag coeficient for a fully submerged cable based on wetted surface area and towed with its axis parallel to the stream is computed by the following formula:

$$D = \tfrac{1}{2}\rho C_f \pi d S V^2 \qquad (1)$$

where: D is drag,

ρ is fluid density,

V is velocity,

d is diameter,

C_f is the drag coefficient, and

S is the length.

To compute C_f for a floating cable from data measured in this experiment two modifications to this equation are necessary. First, the wetted surface area of a floating cable is less than that of a fully submerged cable and is determined by the submergence level when cable weight and buoyancy are in equilibrium. The wetted

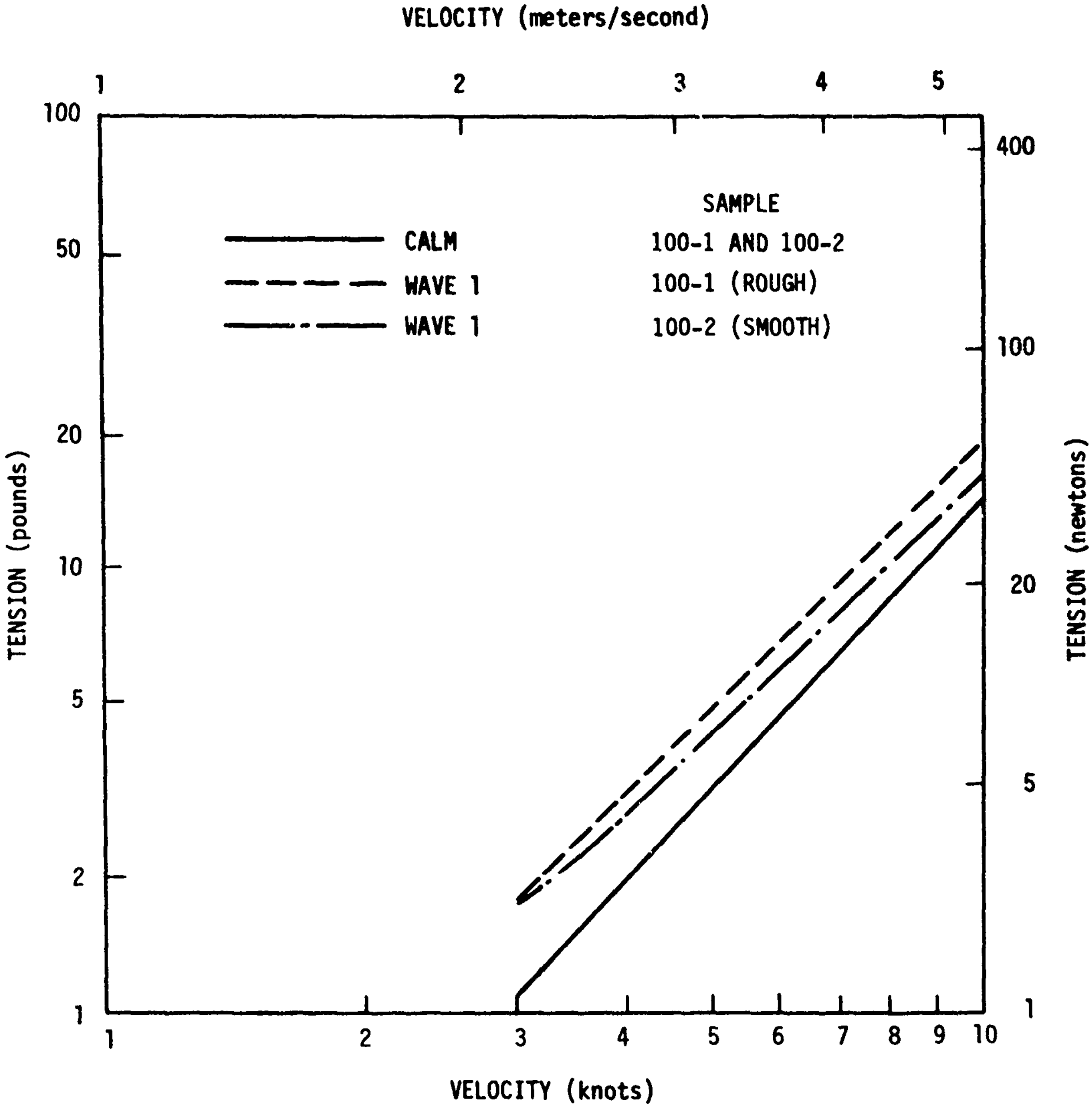

Figure 5 - Tension in the Floating Length as a Function of Velocity for Cables of Different Roughnesses in Calm Water and Wave 1

circumferences Cw for the cable samples were computed and are presented in Table 1. The assumption was made that the drag of the surface length is proportional to the submerged wetted area of the BCA. Cw was assumed to remain constant over the entire surface length. However, in the case of a hybrid tow, the stiffness of the BCA causes the wetted circumference to be greater near the towpoint than at the free end. The value of Cw also could be affected by the surface wave generated by the BCA. This could increase the wetted circumference. Either of these factors could change the values of C_f as a function of Reynolds Number. Since these factors cannot be quantified, they and the effects of water surface tension are neglected in this analysis.

The second modification to the above equation involves compensating for end effects in the drag force measurement. The drag measurement includes certain artificialities attending the experimental method (e.g., short scopes and influence of the dynamometer). Therefore, for Sample 1, the drag of three different lengths was measured. The drag difference computed on a unit length basis $\Delta D_f/\Delta S$ is the characteristic drag of the cable independent of length and free of end effects.

Since only one length of Sample 2 was evaluated, the end effects of Sample 2 were assumed to be the same as for Sample 1 and the $\Delta D_f/\Delta S$ values for Sample 2 were calculated on this basis. The $\Delta D_f/\Delta S$ values are listed in Table A.3 in Appendix A and are plotted versus velocity in Figure 6. Values of $\Delta D_f/\Delta S$ vary approximately as the square of the velocity and are highest for wave 1 and lowest for calm water.

Incorporating these changes into equation (1) the floating length drag coefficient is defined by:

$$C_f = \frac{\Delta D_f/\Delta S}{\frac{1}{2}\rho V^2 Cw} \qquad (2)$$

where: C_f is the floating length drag coefficient,

$\Delta D_f/\Delta S$ is the floating length drag per unit length,

ρ is fluid density,

V is velocity, and

Cw is wetted circumference.

The values of C_f for both samples in the two wave conditions are given in Table 4 and are plotted as a function of Reynolds Number in Figure 7. The drag coefficients are highest for wave 1 and lowest for calm water. The cable roughness seems to have no effect in calm water but is very important in the presence of waves. The general trend is for the drag coefficient to decrease with increasing

Reynolds Number. The cause of the increase in C_f in calm water above a Reynolds Number of 6×10^4 is not known. The errors in the determination of C_f associated with transducer inaccuracies (Table 2) were estimated by the method detailed in Appendix B. The errors range from 9.2 percent at 3 knots (1.5 m/s) to 3.9 percent at 10 knots (5.1 m/s). These errors were calculated based on the calm water data. The errors in C_f for waves are assumed to be approximately equal to the errors in C_f in calm water.

HYBRID TOWS

The experimental data for hydrid tows were used to determine the normal and tangential drag coefficients for the submerged segment of the BCA. These data are listed in Tables A.4 and A.5. The technique used in determining these coefficients is a trial and error computational process in which:

1. A trial set of drag coefficients for the fully submerged segment is assumed;
2. The drag of the floating length represents an end condition;
3. The towing configuration is computed based on the equations and hydrodynamic loading functions proposed by Pode*;
4. The computed configuration is compared with that measured; and
5. Coefficients are changed and the calculations repeated until an acceptable agreement has been reached.

In using this technique the following assumptions are made:

1. The BCA is perfectly flexible (i.e., it cannot support a bending moment) and is inextensible.
2. All forces on the BCA and the BCA itself lie in the gravity/towing velocity plane.
3. The normal component of hydrodynamic force per unit length on the BCA is:

$$F = R\sin^2\phi \tag{3}$$

4. The tangential component of hydrodynamic force is:

$$G = fR \tag{4}$$

where: $$R = \tfrac{1}{2}\rho C_R V^2 d, \tag{5}$$

In determining the end condition for these calculations, i.e., the drag of the floating length, estimates of floating length were obtained from movies of the

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* All references are listed on page 29.

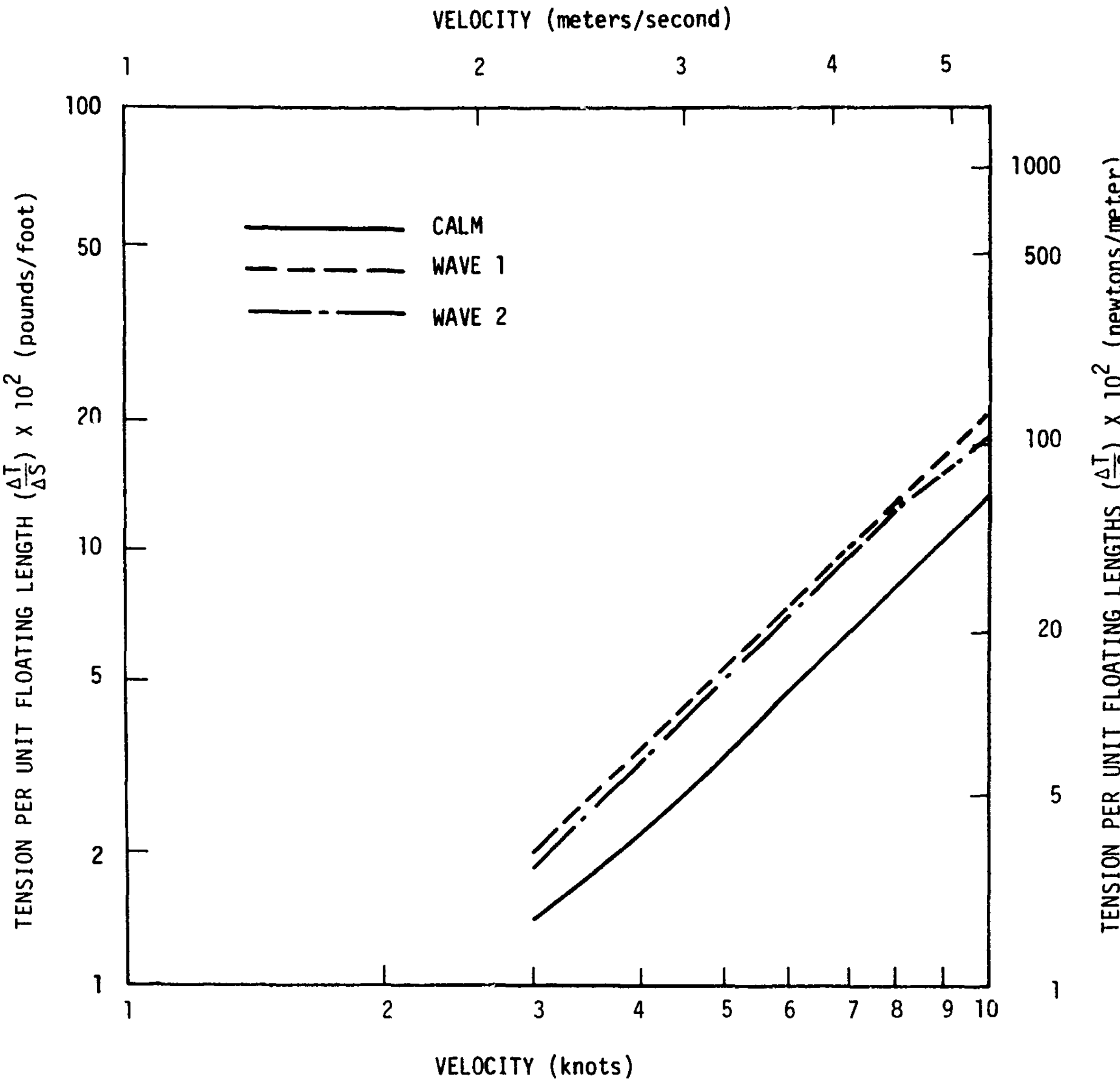


Figure 6 - Drag Per Unit of Floating Length as a Function of Velocity For Sample 1 in Various Wave Conditions

TABLE 4 - FLOATING LENGTH DRAG COEFFICIENT AS A FUNCTION OF VELOCITY FOR VARIOUS WAVE CONDITIONS

Velocity		$C_f \times 10^3$				
		Sample 1			Sample 2	
knots	m/s	Calm Water	Wave 1	Wave 2	Calm Water	Wave 2
3.00	1.53	5.03	7.27	6.56	5.19	6.42
4.00	2.04	4.55	6.94	6.66	4.87	5.84
5.00	2.55	4.29	7.13	6.41	4.58	5.88
6.00	3.06	4.21	6.60	6.25	4.37	5.70
7.00	3.57	4.19	6.68	6.39	4.41	5.55
8.00	4.08	4.41	6.84	6.26	4.41	5.55
9.00	4.59	4.36	6.67	6.07	4.43	5.41
10.00	5.10	4.84	6.62	5.96	4.56	5.38

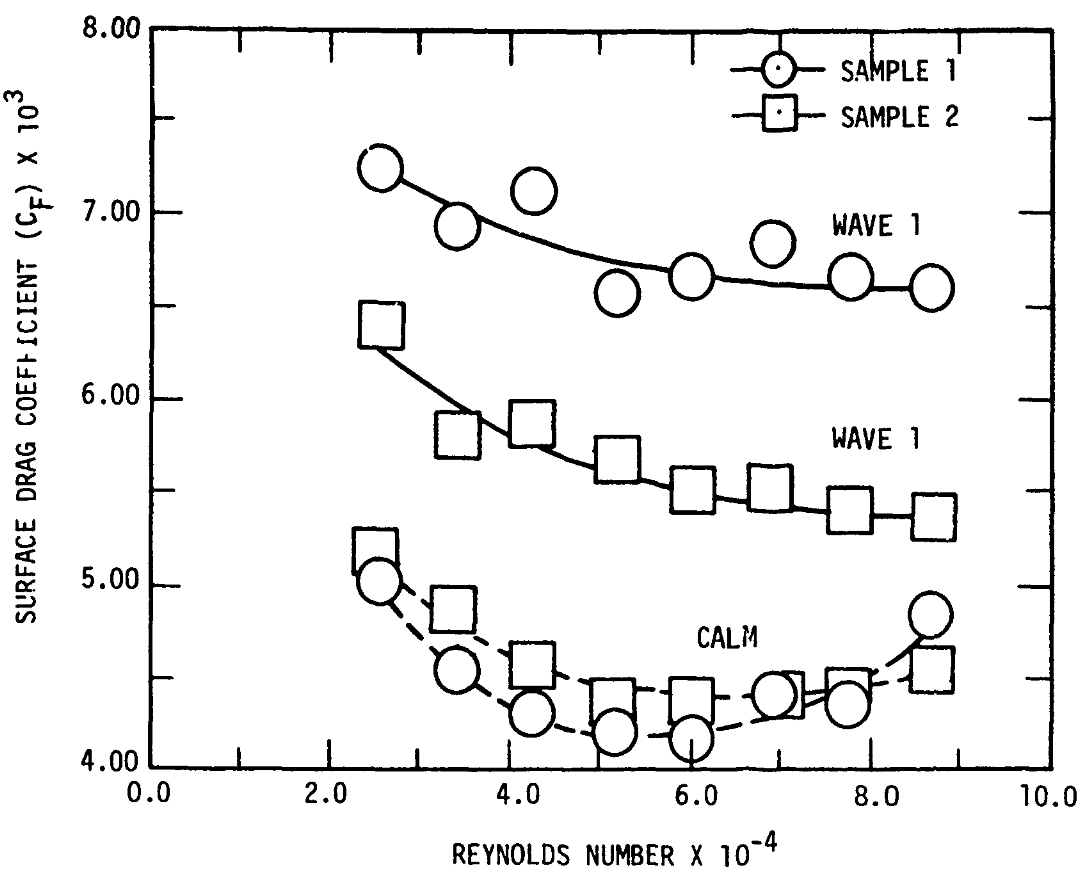


Figure 7 - Floating Length Drag Coefficient
as a Function of Reynolds Number

surface region as the BCA passed the camera. At the lower speeds, the BCA approached the surface at a relatively steep angle, and the point at which the BCA reached the surface was well defined. At high speeds, however, the angle of the BCA was very small, and the exact point at which it reached the surface could not be accurately determined. The uncertainty in determining the surface length is designated ΔSL in Table A.4. Estimates of tension developed by the floating length segment were obtained by multiplying the measured floating length by the corresponding value of $\Delta D_f/\Delta S$ (Table A.3) at the same velocity. Thus the uncertainty in surface length tension ΔD_f is proportional to the uncertainty in the length of the floating segment.

In the trial and error process of determining C_R and f, these coefficients were varied until the predicted towpoint tension and towpoint depth agreed with the measured values to within ±0.05 lb (0.22 N) and ±0.04 in. (1.0 mm), respectively, for a given overall BCA length and towing speed. Values for C_R and f were thus determined using the average values of the measured input parameters (Table 2). The input parameters then were varied to the stated limit of measurement accuracy, first in the direction which increase the values of C_R and f. Catenary predictions made with these input values determined the maximum values of C_R and f due to experimental measurement inaccuracies. The procedure then was repeated varying the tolerances in the other direction to determine the minimum values of C_R and f. For each run, the average value of the maximum and minimum C_R and f was calculated, and these averages are presented in Table 5. The differences between these averages and either the maximum or minimum values of C_R and f are presented as ΔC_R and Δf. The average values are plotted in Figure 8.

Experimental data for hybrid tows in waves 1 and 2 are listed in Table A.5 in Appendix A. The corresponding values of C_R and f were generated by the same procedure used for the calm water drag coefficients and are listed in Table 6. Due to the presence of waves, there was no constant depth waterline which could be used to determine the surface length of BCA. Therefore, the length of BCA on the surface in waves was defined in the following manner. First, a line was stretched along the movie screen on which the film was projected at the position corresponding to the depth of the deepest wave trough. The length at which the BCA crossed this line was determined, and the remaining length outboard was regarded as an upper limit on surface length. The second step involved stretching a line across the screen at the point corresponding to the water surface in calm water. The length of the BCA

TABLE 5 - SUBMERGED SEGMENT DRAG COEFFICIENTS IN CALM WATER

Run	Sample Length		Strut Depth		Speed		C_R	ΔC_R	f	Δf
	ft	m	ft	m	knot	m/s				
5	100.4	30.60	3.0	.91	3.0	1.53	0.65	0.14	0.0212	0.0082
6					4.0	2.04	1.02	0.14	0.0187	0.0029
8					5.0	2.55	2.05	0.17	0.0181	0.0009
10					7.0	3.57	1.98	0.16	0.0185	0.0001
11			3.0	.91	8.0	4.08	1.88	0.15	0.0168	0.0000
12			5.0	1.52	3.0	1.53	1.11	0.13	0.0237	0.0044
13					4.0	2.04	1.15	0.11	0.0215	0.0015
14					5.0	2.55	1.09	0.10	0.0203	0.0007
15					6.0	3.06	1.17	0.09	0.0192	0.0002
16	100.4	30.60	5.0	1.52	7.0	3.57	1.37	0.10	0.0180	0.0180
20	400.7	122.13	3.0	.91	3.0	1.53	--	--	0.0129	0.0046
21					4.0	2.04	0.32	0.23	0.0156	0.0020
22					5.0	2.55	0.39	0.20	0.0170	0.0010
23					6.0	3.06	0.94	0.23	0.0181	0.0003
24					7.0	3.57	1.28	0.23	0.0163	0.0001
25	100.7	122.13			8.0	4.08	1.59	0.23	0.0153	0.0000
34	400.8	122.16			9.0	4.59	2.86	0.60	0.0182	0.0000
35	400.8	122.16	3.0	.91	10.0	5.10	2.32	0.59	0.0158	0.0001
26	400.7	122.13	5.0	1.52	3.0	1.53	0.30	0.18	0.0218	0.0034
27					4.0	2.04	0.51	0.16	0.0217	0.0012
29					6.0	3.06	1.15	0.16	0.0191	0.0000
30					7.0	3.57	1.46	0.19	0.0162	0.0001
31					8.0	4.08	1.44	0.24	0.0146	0.0000
36					9.0	4.59	2.46	0.33	0.0181	0.0001
37	400.7	122.13			10.0	5.10	2.82	0.32	0.0151	0.0003
74	100.4	30.60			3.0	1.53	1.20	0.24	0.0239	0.0048
75	(100-3)				4.0	2.04	1.30	0.21	0.0186	0.0018
76					5.0	2.55	1.37	0.18	0.0168	0.0008
77					6.0	3.06	1.34	0.16	0.0150	0.0004
78	(100-3)	30.60	5.0	1.52	7.0	3.57	1.69	0.15	0.0142	0.0003

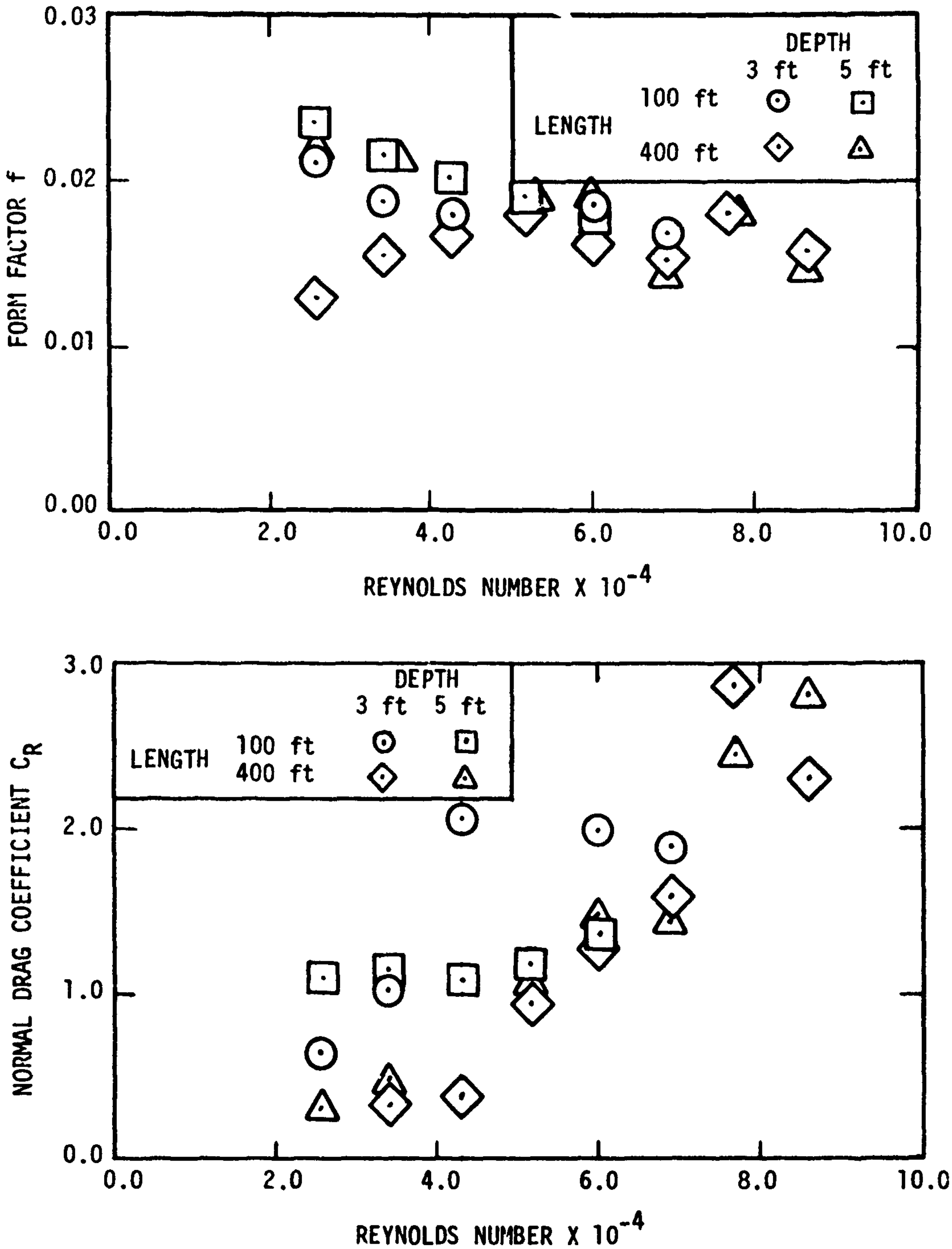


Figure 8 - Submerged Segment Drag Coefficient as a Function of Reynolds Number in Calm Water for Sample 1

TABLE 6 - SUBMERGED SEGMENT DRAG COEFFICIENTS IN WAVES 1 and 2

Run #	Sample Length ft	Sample Length m	Strut Depth ft	Strut Depth m	Speed knot	Speed m/s	C_R	ΔC_R	f	Δf
43	400.8	122.16	5.0	1.52	7.0	3.57	2.50	0.75	0.0157	0.0000
44					8.0	4.08	2.08	0.66	0.0162	0.0000
45					9.0	4.59	1.75	0.59	0.0222	--
46					10.0	5.10	2.70	0.54	0.0185	0.0008
47					7.0	3.57	1.29	0.73	0.0148	0.0002
48					8.0	4.08	2.93	0.69	0.0238	0.0047
49					9.0	4.59	2.94	0.62	0.0186	0.0017
50	400.8	122.16			10.0	5.10	--	--	--	--
54	400.7	122.13			3.0	1.53	0.76	--	0.0149	0.0004
55					4.0	2.04	2.06	0.45	0.0167	0.0001
56					5.0	2.55	0.69	0.30	0.0162	0.0001
57					6.0	3.06	1.10	0.28	0.0146	0.0002
60					3.0	1.53	0.46	0.40	0.0123	0.0032
61					5.0	2.56	0.81	0.30	0.0138	0.0004
62					6.0	3.06	1.59	0.52	0.0149	0.0001
81					3.0	1.53	1.60	0.30	0.0184	0.0037
82					3.0	1.53	1.47	0.29	0.0231	0.0038
95					3.0	1.53	0.87	0.22	0.0177	0.0048
96					4.0	2.04	0.92	0.18	0.0193	0.0019
97					5.0	2.55	1.09	0.17	0.0191	0.0008
98					6.0	3.06	1.20	0.16	0.0182	0.0003
99					7.0	3.57	1.43	0.22	0.0173	0.0001
100	400.7	122.13			3.0	1.53	1.30	0.27	0.0197	0.0041
101	100.3	30.57			4.0	2.04	1.03	0.19	0.0202	0.0017
103					6.0	3.06	1.43	0.17	0.0175	0.0003
104			5.0	1.52	6.0	3.06	1.77	0.21	0.0178	0.0002
106			3.0	.91	3.0	1.53	--	--	0.0139	--
107					5.0	2.55	0.16	--	0.0168	0.0012
108	100.3	30.57	3.0	.91	7.0	3.57	0.43	0.16	0.0165	0.0003

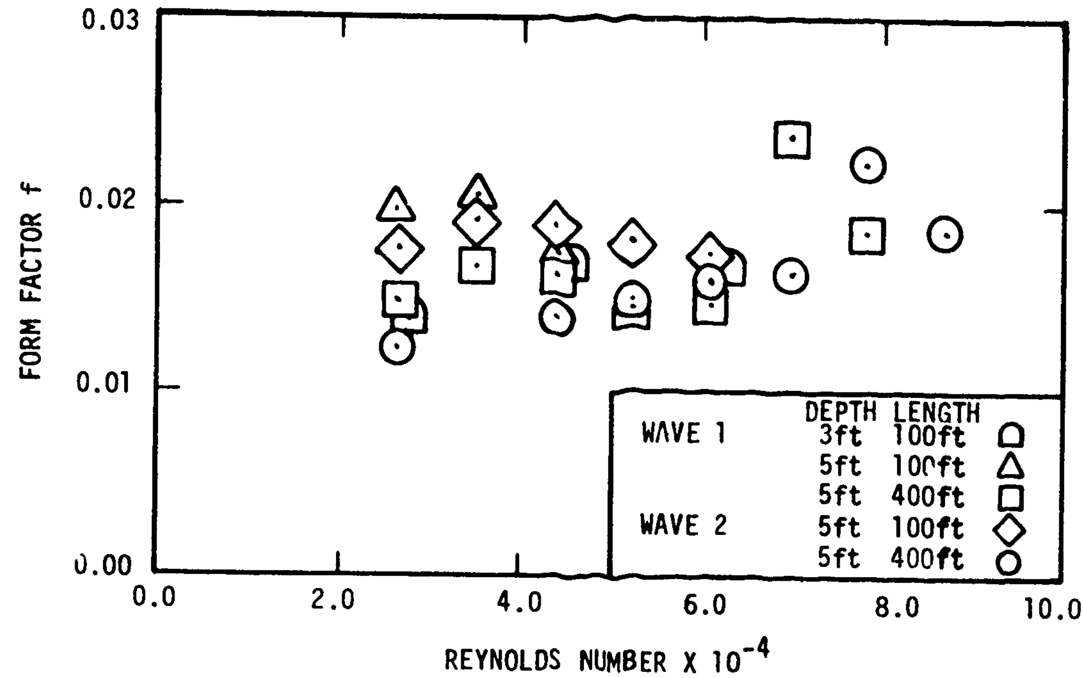
outboard of this line was regarded as a lower limit on the surface length. The actual surface length was taken as the average of these two values, and ΔS_f is the difference between the average and extreme values.

Examining Figure 8 showing C_R and f in calm water, it is seen that different drag coefficients were generated for different lengths of the same BCA at the same velocity. The drag coefficients also seem to be a function of towpoint depth. Furthermore, there is no consistent pattern to this variation. For example, values of C_R for the 400-ft (122-m) BCA at a towpoint depth of 5 ft (1.5 m) are lower than values of C_R for a 100-ft (30-m) BCA at a 5-ft (1.5 m) depth at Reynolds Numbers below 5×10^4 but are higher at Reynolds Numbers above 6×10^4. There is a general trend for C_R to increase with increasing Reynolds Number, while f seems to remain fairly constant above Rn = 5×10^4.

The values of C_R and f in waves 1 and 2 are plotted in Figure 9. Trends here are not as well-defined as they were in calm water. Again, there is no consistent pattern to the distribution of drag coefficients for a given Reynolds Number. The range of values covered for both the normal and tangential drag coefficients in calm water corresponds closely to the range of values for C_R and f in wave conditions.

There are a number of possible explanations for the discrepancies in the data. First, the computer program used to predict C_R and f assumes that the BCA is completely flexible and cannot support a bending moment. The actual BCA is quite stiff, however, especially when used in short lengths as was the case for this evaluation. The effect of this stiffness is that the curvature of the actual sample due to the hydrodynamic forces is less than the curvature predicted by the program. Thus, for a given sample length, surface length and velocity, the program predicts a deeper towpoint depth than was actually used. To make the predicted end conditions (depth and tension) match the actual end conditions, the program underpredicts the values of the normal drag coefficient. Since a prediction program incorporating the effects of bending stiffness was not available, the magnitude of this underprediction could not be determined.

The second possible reason for the data scatter is the definition of the surface length. The curvature of the BCA is determined to a large extent by the tension of the floating length, which in turn is proportional to the floating length. The definition of floating length for the analysis was arbitrary, and the BCA was considered to be on the surface when the upper edge of the BCA touched the



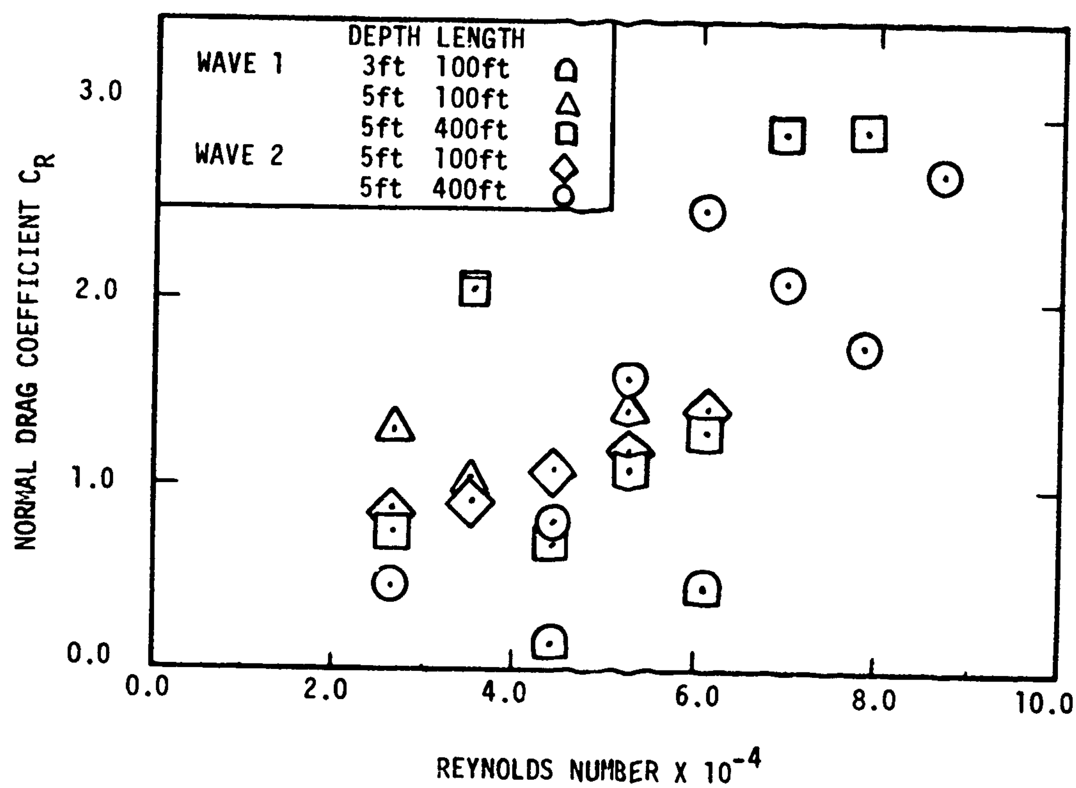


Figure 9 - Submerged Segment Drag Coefficient as a Function of Reynolds Number in Waves 1 and 2

water surface. At this point, however, a large portion of the BCA was still underwater and may be considered to be subjected to the submerged segment drag coefficients. In addition, a surface wave was generated by the section of the BCA at and on the water surface. This surface wave changes the point at which the BCA is considered to be on the surface.

CONCLUSIONS

On the basis of the data analysis described in this report, the following conclusions are drawn:

1. For all BCA samples in all wave conditions, the tension developed by the floating length is proportional to the square of the velocity.

2. Cable roughness does not seem to affect the surface drag coefficients in calm water but has a large effect in waves.

3. The surface drag coefficients are highest in wave 1 and lowest in calm water.

4. In general, the floating length drag coefficients decrease with increasing Reynolds Number.

5. The BCA samples evaluated exhibited considerable "memory" and cannot be considered perfectly flexible. Therefore, the assumptions on which the computer analysis was based are not completely valid.

6. The data spread for submerged normal and tangential drag coefficients is approximately the same in calm water and in waves.

REFERENCES

1. Pode, L., "Tables for Computing the Equilibrium Configuration of a Flexible Cable in a Uniform Stream," David Taylor Model Basin Report 687 (March 1951).

2. "Handbook of Ocean and Underwater Engineering," pp. 11-98, Myers, John, Holm, Carl and McAllister, Raymond, McGraw-Hill Book Company (1969).

APPENDIX A
EXPERIMENTAL DATA

The tabulated results of the buoyant-cable antenna evaluation are presented in Tables A.1 through A.5. The results of the surface towing tests in calm water and in waves are presented in Table A.1. The upper table on each page presents the average data for the entire run as taken from the computer analysis. The lower table on each page presents the data adjusted to reflect even velocities based on velocity-squared scaling. This adjustment is required for the calculation of $\Delta D_f/\Delta S$ involved in the determination of surface and submerged drag coefficients. The wetted lengths of cable measured in the surface towing tests are presented in Table A.2. These lengths are used to calculate the values of $\Delta D_f/\Delta S$. The corresponding values of tension per unit floating length as a function of velocity for various wave conditions are presented in Table A.3. The experimental data for the hybrid tows, consisting of a submerged towpoint with both submerged and floating BCA, are listed in Table A.4 for calm water. Similar data for hybrid tows in waves are listed in Table A.5.

TABLE A.1 - RESULTS OF SURFACE TOWING TESTS

TABLE A.1A - RESULTS OF SURFACE TOWING TESTS FOR SAMPLE 100-1

Measured Data:

Calm Water				Wave 1				Wave 2			
Velocity		Tension		Velocity		Tension		Velocity		Tension	
knots	m/s	lb	N	knots	m/s	lb	N	knots	m/s	lb	N
3.00	1.53	1.12	4.98	3.03	1.55	1.86	8.28	3.02	1.54	1.47	6.54
4.00	2.04	2.03	9.03	4.02	2.05	3.23	14.37	3.99	2.03	2.63	11.70
4.98	2.54	3.23	14.37	4.98	2.54	4.93	21.94	4.98	2.54	4.34	19.31
5.98	3.05	4.68	20.83	6.00	3.06	7.09	31.55	5.98	3.05	6.29	27.99
6.99	*3.56*	*6.71*	*29.86*	*6.97*	*3.55*	*9.69*	*43.12*	*7.00*	*3.57*	*9.24*	*41.12*
7.97	4.06	8.80	39.16	7.99	4.07	12.87	57.27	8.02	4.09	12.29	54.69
8.97	4.57	11.10	49.40	9.03	4.60	15.76	70.13	9.02	4.60	15.49	68.93
9.98	5.09	13.61	60.56	10.01	5.11	19.66	87.49	9.96	5.08	18.85	83.88

Corrected Data:

Calm Water				Wave 1				Wave 2			
Velocity		Tension		Velocity		Tension		Velocity		Tension	
knots	m/s	lb	N	knots	m/s	lb	N	knots	m/s	lb	N
3.00	1.53	1.12	4.98	3.00	1.53	1.82	8.10	3.00	1.53	1.45	6.45
4.00	2.04	2.03	9.03	4.00	2.04	3.21	14.28	4.00	2.04	2.64	11.75
5.00	2.55	3.25	14.46	5.00	2.55	4.97	22.12	5.00	2.55	4.38	19.49
6.00	3.06	4.71	20.96	6.00	3.06	7.09	31.55	6.00	3.06	6.33	28.17
7.00	3.57	6.74	30.00	7.00	3.57	9.76	43.43	7.00	3.57	9.24	41.12
8.00	4.08	8.86	39.43	8.00	4.08	12.90	57.41	8.00	4.08	12.23	54.42
9.00	4.59	11.17	49.71	9.00	4.59	15.67	69.73	9.00	4.59	15.43	68.66
10.00	5.10	13.65	60.74	10.00	5.10	19.63	87.35	10.00	5.10	19.02	84.64

TABLE A.1 (Continued)

TABLE A.1B - RESULTS OF SURFACE TOWING TESTS FOR SAMPLE 200-1

Measured Data:

Calm Water				Wave 1				Wave 2			
Velocity		Tension		Velocity		Tension		Velocity		Tension	
knots	m/s	lb	N	knots	m/s	lb	N	knots	m/s	lb	N
3.00	1.53	2.71	12.06	3.02	1.63	3.88	17.27	2.99	1.52	3.39	15.09
3.99	2.03	4.68	20.83	3.98	2.03	6.68	29.73	3.98	2.03	5.97	26.57
4.97	2.53	7.16	31.86	4.97	2.53	10.32	45.92	4.97	2.53	9.46	42.10
5.97	3.04	10.06	44.77	5.98	3.05	14.67	65.28	5.98	3.05	13.90	61.86
6.98	3.56	13.49	60.03	6.95	3.54	19.66	87.49	6.99	3.56	18.23	81.12
7.99	4.07	18.28	81.35	8.01	4.09	24.22	107.78	7.99	4.07	23.98	106.71
9.01	4.60	23.02	102.44	8.99	4.58	30.61	136.21	9.01	4.60	30.12	134.03
10.00	5.10	28.54	127.00	9.99	5.09	37.97	168.97	10.01	5.11	36.41	162.02

Corrected Data:

Calm Water				Wave 1				Wave 2			
Velocity		Tension		Velocity		Tension		Velocity		Tension	
knots	m/s	lb	N	knots	m/s	lb	N	knots	m/s	lb	N
3.00	1.53	2.72	12.10	3.00	1.53	3.82	17.00	3.00	1.53	3.42	15.22
4.00	2.04	4.69	20.87	4.00	2.04	6.75	30.04	4.00	2.04	6.03	26.83
5.00	2.55	7.23	32.17	5.00	2.55	10.44	46.46	5.00	2.55	9.57	42.59
6.00	3.06	10.14	45.12	6.00	3.06	14.75	65.64	6.00	3.06	13.98	62.21
7.00	3.57	13.55	60.30	7.00	3.57	19.92	88.64	7.00	3.57	18.25	81.21
8.00	4.08	18.31	81.48	8.00	4.08	24.17	107.56	8.00	4.08	24.04	106.98
9.00	4.59	22.96	102.17	9.00	4.59	30.67	136.48	9.00	4.59	30.07	133.81
10.00	5.10	28.51	126.87	10.00	5.10	38.06	169.37	10.00	5.10	36.34	161.71

TABLE A.1 (Continued)

TABLE A.1C - RESULTS OF SURFACE TOWING TESTS FOR SAMPLE 400-1

Measured Data:

Calm Water				Wave 1				Wave 2			
Velocity		Tension		Velocity		Tension		Velocity		Tension	
knots	m/s	lb	N	knots	m/s	lb	N	knots	m/s	lb	N
3.00	1.53	5.43	24.16	3.02	1.55	8.07	35.91	3.01	1.54	7.06	31.42
4.01	2.04	8.98	39.96	4.00	2.04	13.65	60.74	4.01	2.05	12.71	56.56
5.00	2.55	13.40	59.63	4.98	2.54	21.48	95.59	4.97	2.53	19.18	85.35
6.00	3.06	19.02	84.64	5.95	3.03	28.84	128.34	5.96	3.04	27.13	120.73
7.02	3.58	26.08	116.06	6.97	3.55	39.90	177.56	7.02	3.58	38.54	171.50
7.99	4.07	35.08	156.11	7.99	4.07	53.07	236.16	8.00	4.08	49.34	219.56
9.02	4.60	44.25	196.91	9.01	4.60	65.63	292.05	8.98	4.59	60.68	270.03
10.01	5.11	58.48	260.24	10.02	5.11	80.78	359.47	9.97	5.08	73.52	327.16

Corrected Data:

Calm Water				Wave 1				Wave 2			
Velocity		Tension		Velocity		Tension		Velocity		Tension	
knots	m/s	lb	N	knots	m/s	lb	N	knots	m/s	lb	N
3.00	1.53	5.42	24.12	3.00	1.53	7.96	35.42	3.00	1.53	7.03	31.28
4.00	2.04	8.94	39.78	4.00	2.04	13.66	60.79	4.00	2.04	12.67	56.38
5.00	2.55	13.42	59.72	5.00	2.55	21.66	96.39	5.00	2.55	19.43	86.46
6.00	3.06	19.01	84.59	6.00	3.06	29.33	130.52	6.00	3.06	27.47	122.24
7.00	3.57	25.96	115.52	7.00	3.57	40.29	179.29	7.00	3.57	38.28	170.35
8.00	4.08	35.20	156.64	8.00	4.08	53.16	236.56	8.00	4.08	49.32	219.47
9.00	4.59	44.07	196.11	9.00	4.59	65.45	291.25	9.00	4.59	60.93	271.14
10.00	5.10	58.36	259.70	10.00	5.10	80.42	357.87	10.00	5.10	73.94	329.03

TABLE A.1 (Continued)

TABLE A.1D - RESULTS OF SURFACE TOWING TESTS FOR SAMPLE 100-2

Measured Data:

Calm Water				Wave 1			
Velocity		Tension		Velocity		Tension	
knots	m/s	lb	N	knots	m/s	lb	N
3.01	1.54	1.45	6.45	3.00	1.53	1.78	7.92
3.99	2.03	2.38	10.60	3.98	2.03	2.84	12.64
4.97	2.53	3.46	15.40	4.98	2.54	4.47	19.89
5.98	3.05	4.79	21.32	5.97	3.04	6.21	27.63
6.98	3.56	6.54	29.10	7.00	3.57	8.27	36.80
7.98	4.07	8.53	37.96	7.99	4.07	10.74	47.79
9.01	4.60	10.89	48.46	9.02	4.60	13.31	59.23
9.97	5.08	13.69	60.92	10.02	5.11	16.31	72.58

Corrected Data:

Calm Water				Wave 1			
Velocity		Tension		Velocity		Tension	
knots	m/s	lb	N	knots	m/s	lb	N
3.00	1.53	1.44	6.41	3.00	1.53	1.78	7.92
4.00	2.04	2.39	10.64	4.00	2.04	2.87	12.77
5.00	2.55	3.50	15.58	5.00	2.55	4.50	20.03
6.00	3.06	4.81	21.40	6.00	3.06	6.26	27.86
7.00	3.57	6.58	29.28	7.00	3.57	8.27	36.80
8.00	4.08	8.57	38.14	8.00	4.08	10.78	47.97
9.00	4.59	10.86	48.33	9.00	4.59	13.26	59.01
10.00	5.10	13.77	61.28	10.00	5.10	16.25	72.31

TABLE A.2 - WETTED LENGTH FOR SURFACE TESTS

Velocity knots	Velocity m/s	Sample 100-1 and 100-2 ft	Sample 100-1 and 100-2 m	Sample 200-1 ft	Sample 200-1 m	Sample 400-1 ft	Sample 400-1 m
3.0	1.53	99.7	30.75	200.0	61.68	400.0	123.36
4.0	2.04	99.5	30.69	199.5	61.53	399.0	123.05
5.0	2.55	99.2	30.59	199.0	61.37	398.0	122.74
6.0	3.06	99.0	30.53	198.5	61.22	397.0	122.43
7.0	3.57	98.7	30.44	198.0	61.06	396.0	122.13
8.0	4.08	98.5	30.38	197.5	60.91	395.0	121.82
9.0	4.59	98.2	30.28	197.0	60.75	394.0	121.51
10.0	5.10	98.0	30.22	196.5	60.60	393.0	121.20

Note: Length measurements $\pm$ 0.5 ft.

TABLE A.3 - TENSION PER UNIT FLOATING LENGTH AS A FUNCTION OF VELOCITY FOR VARIOUS WAVE CONDITIONS

Velocity		Sample I						Sample 2			
		Calm Water		Wave 1		Wave 2		Calm Water		Wave 1	
knots	m/s	lb/ft	N/m	lb/ft	N/m	lb/ft	N/m	lb/ft	N/m	lb/ft	N/m
3.00	1.53	0.0142	.2072	0.0205	.2992	0.0185	.2700	0.0144	.2101	0.0178	.2598
4.00	2.04	0.0228	.3327	0.0348	.5078	0.0334	.4874	0.0240	.3502	0.0288	.4203
5.00	2.55	0.0336	.4903	0.0559	.8158	0.0502	.7326	0.0353	.5151	0.0453	.6611
6.00	3.06	0.0475	.6932	0.0745	1.0872	0.0705	1.0288	0.0485	.7078	0.0632	.9223
7.00	3.57	0.0644	.9398	0.1027	1.4987	0.0981	1.4316	0.0666	.9719	0.0837	1.2214
8.00	4.08	0.0884	1.2900	0.1373	2.0099	0.1255	1.8315	0.0870	1.2696	0.1094	1.5965
9.00	4.59	0.1106	1.6140	0.1695	2.4736	0.1542	2.2503	0.1105	1.6126	0.1350	1.9701
10.00	5.10	0.1516	2.2123	0.2074	3.0267	0.1869	2.7275	0.1405	2.0504	0.1658	2.4195

TABLES A.4 - EXPERIMENTAL DATA IN CALM WATER FOR HYBRID TOWS

Run #	Sample Length ft	Sample Length m	Strut Depth ft ±0.005	Strut Depth m ±.002	Speed knot ±0.03	Speed m/s ±.02	Surface Length ft	Surface Length m	ΔSL ft	ΔSL m	Surface Tension lb	Surface Tension N	ΔT lb	ΔT N	TowPt Tension lb	TowPt Tension N	σtp Tension lb	σtp Tension N
5	100.4	30.60	3.0	.91	3.0	1.53	78.8	20.02	0.4	.12	1.12	4.98	0.01	.04	1.78	7.92	0.05	.22
6	±0.02	±.006			4.0	2.04	69.0	21.03	0.6	.30	1.57	6.99	0.03	.04	3.03	13.48	0.11	.49
8					5.0	2.55	49.7	15.15	0.3	.09	1.67	7.43	0.01	.04	5.15	22.92	0.23	1.02
10					7.0	3.57	31.9	9.72	0.5	.15	2.05	9.12	0.03	.13	11.36	50.55	0.26	1.16
11			3.0	.91	8.0	4.08	24.9	7.59	0.5	.15	2.20	9.79	0.04	.18	14.38	63.99	0.43	1.91
12			5.0	1.52	3.0	1.53	61.9	18.87	0.5	.15	0.88	3.92	0.01	.04	2.21	9.83	0.14	.62
13					4.0	2.04	49.4	15.06	0.5	.15	1.13	5.03	0.01	.04	3.86	17.18	0.12	.53
14					5.0	2.55	39.4	12.01	0.5	.15	1.33	5.92	0.01	.04	6.07	27.01	0.18	.80
15					6.0	3.06	25.9	7.89	0.5	.15	1.23	5.47	0.02	.09	9.04	40.23	0.23	1.02
16	±0.02	±.006	5.0	1.52	7.0	3.57	8.4	2.56	0.5	.15	0.54	2.40	0.03	.13	12.76	56.78	0.24	1.07
20	400.7	122.13	3.0	.91	3.0	1.53	368.5	112.32	0.5	.15	5.23	23.27	0.01	.04	5.86	26.08	0.24	1.07
21	±0.08	±.02			4.0	2.04	356.5	108.66	0.5	.15	8.13	36.18	0.01	.04	9.81	43.65	0.24	1.07
22					5.0	2.55	346.5	105.61	0.5	.15	11.64	51.80	0.01	.04	15.14	67.37	0.28	1.25
23					6.0	3.06	331.5	101.04	0.5	.15	15.74	70.04	0.02	.09	22.54	100.30	0.57	2.54
24					7.0	3.57	317.5	96.77	0.5	.15	20.44	90.96	0.03	.13	30.41	135.32	0.26	1.16
25	±0.08	±.02			8.0	4.08	301.5	91.90	0.5	.15	26.65	118.59	0.04	.18	41.29	183.74	0.64	2.85
34	400.8	122.16			9.0	4.59	275.0	83.82	4.0	1.22	30.41	135.32	0.45	2.00	58.28	259.35	0.51	2.27
35	±0.08	±.02	3.0	.91	10.0	5.10	266.0	81.08	5.0	1.52	39.82	177.20	0.26	5.14	72.04	320.58	0.98	4.36
26	400.7	122.13	5.0	1.52	3.0	1.53	354.5	108.05	0.5	.15	5.04	22.43	0.01	.04	6.49	28.88	0.13	.58
27	±0.08	±.02			4.0	2.04	339.5	103.48	0.5	.15	7.74	34.44	0.01	.04	11.01	48.99	0.14	.62
29	±0.08	±.02			6.0	3.06	301.5	91.90	0.5	.15	14.31	63.68	0.02	.09	24.63	109.60	0.30	1.33
30	±0.08	±.02			7.0	3.57	281.0	85.65	1.0	.30	18.10	80.55	0.06	.27	32.37	144.05	0.32	1.42
31	400.7	122.13			8.0	4.08	263.5	80.31	2.5	.76	23.29	103.64	0.22	.98	42.61	189.61	0.49	2.18
36	400.8	122.16			9.0	4.59	221.0	67.36	5.0	1.52	24.44	108.76	0.55	2.45	64.17	285.56	0.56	2.49
37	±0.08	±.02			10.0	5.10	191.0	58.22	5.0	1.52	28.95	128.83	0.76	3.38	76.99	342.61	0.80	3.56
74	100.4	30.60			3.0	1.53	60.0	18.29	2.0	.61	0.85	3.78	0.03	.13	2.22	9.88	0.22	.98
75					4.0	2.04	46.0	14.02	2.0	.61	1.05	4.67	0.05	.22	3.53	15.71	0.12	.53
76					5.0	2.55	32.0	9.75	2.0	.61	1.07	4.76	0.07	.31	5.41	24.07	0.19	.85
77					6.0	3.06	20.0	6.10	2.0	.61	0.95	4.23	0.10	.44	7.49	33.33	0.19	.85
78	100.04	30.60	5.0	1.52	7.0	3.57	0.0	0.00	0.0	0.00	0.00	0.00	0.00	0.00	10.56	46.99	0.99	4.40

TABLE A.5 - EXPERIMENTAL DATA IN WAVES 1 AND 2 FOR HYBRID TOWS

Run #	Sample Length ft	Sample Length m	Strut Depth ft ±0.005	Strut Depth m ±.002	Speed knot ±0.03	Speed m/s ±.02	Wave Period sec	Avg Wave Height in.	Avg Wave Height cm	Surface Length ft	Surface Length m	ΔSL ft	ΔSL m	TowPT Tension lb	TowPT Tension N	σtp Tension lb	σtp Tension N
43	400.8	122.16	5.0	1.52	7.0	3.57	2.43	3.01	7.65	265	80.77	25	7.62	41.89	186.33	0.97	4.31
44					8.0	4.08				245	74.68	15	4.57	55.07	244.95	1.05	4.67
45					9.0	4.59				260	79.25	20	6.10	69.57	309.45	1.42	6.32
46					10.0	5.10	2.43	3.01	7.65	210	64.00	30	9.14	86.30	383.86	1.41	6.27
47					7.0	3.57	1.40	2.40	6.10	280	85.34	20	6.10	43.29	192.55	0.58	2.58
48					8.0	4.08				235	71.63	25	7.62	55.52	246.95	0.72	3.20
49					9.0	4.59				220	67.06	40	12.19	70.05	311.58	1.00	4.45
50	400.8	122.16			10.0	5.10				---	---	--	---	---	---	--	--
54	400.7	122.13			3.0	1.53				349	106.38	5	1.52	9.02	40.12	0.38	1.69
55					4.0	2.04				324	98.76	12	3.66	14.86	66.10	0.39	1.73
56					5.0	2.55				314	95.71	7	2.13	22.47	99.95	0.49	2.18
57					6.0	3.06	1.40	2.40	6.10	295	89.92	15	4.57	31.64	140.73	0.48	2.14
60					3.0	1.53	2.43	3.01	7.65	351	106.98	5	1.52	7.39	32.87	0.92	4.09
61					5.0	2.55	2.43	3.01	7.65	320	97.54	10	3.05	20.30	90.29	0.78	3.47
62	400.7	122.13			6.0	3.06	2.43	3.01	7.65	295	89.92	15	4.57	29.42	130.86	0.81	3.60
81	100.3	30.57			3.0	1.53	1.40	2.40	6.10	54	16.46	2	.61	2.34	10.41	0.18	0.80
82					3.0	1.53	1.40	2.40	6.10	56	17.07	2	.61	2.62	11.65	0.19	0.85
95					3.0	1.53	2.43	3.01	7.65	64	19.51	2	.61	2.14	9.52	0.15	0.67
96					4.0	2.04				52	15.85	2	.61	4.04	17.97	0.24	1.07
97					5.0	2.55				38	11.58	2	.61	6.43	28.60	0.19	0.85
98					6.0	3.06				24	7.32	2	.61	9.21	40.97	0.41	1.82
99					7.0	3.57	2.43	3.01	7.65	6	1.83	4	1.22	12.62	56.13	0.38	1.69
100					3.0	1.53	1.40	2.40	6.10	58	17.68	2	.61	2.40	10.68	0.19	0.85
101					4.0	2.04				50	15.24	2	.61	4.26	18.95	0.18	0.80
103					6.0	3.06				18	5.49	2	.61	9.20	40.92	0.2[illegible]	1.02
104			5.0	1.52	6.0	3.06				10	3.05	2	.61	9.49	42.21	0.32	1.42
106			3.0	.91	3.0	1.53				78	23.77	2	.61	2.32	10.32	0.20	0.89
107			3.0	.91	5.0	2.55				56	17.07	2	.61	5.97	26.55	0.22	0.98
108	100.3	30.57	3.0	.91	7.0	3.57	1.40	2.40	6.10	38	11.58	4	1.22	11.48	51.02	0.29	1.29

APPENDIX B
ERROR ANALYSIS OF FLOATING LENGTH DRAG COEFFICIENTS

In order to determine the inaccuracies in the calculated values of the surface drag coefficient, C_f, it is necessary to determine the contribution due to each individual measurement used in the equation for C_f. As stated in the "Experimental Results and Discussion" section of this report, the surface drag coefficient C_f is defined as:

$$C_f = \frac{\Delta D_f/\Delta S}{\frac{1}{2}\rho V^2 Cw} .$$

The experimental inaccuracies for each parameter in the equation are listed in Table B.1.

TABLE B.1 - PARAMETERS AND ACCURACIES USED IN THE DETERMINATION OF THE FLOATING LENGTH DRAG COEFFICIENT

Parameter	Value	Accuracy
Tension Per Unit Length, $\frac{\Delta T}{\Delta S}$	As Stated	0.00118 to 0.00186 lb/ft
		0.01722 to 0.02714 N/m
Water Density, ρ	1.9362 $slug/ft^3$	$\pm$ 0.02 $slug/ft^3$
		$\pm$ 10.3 kg/m^3
Velocity, V	As Stated	$\pm$ 0.02 ft/sec
		$\pm$ 0.01 m/sec
Wetted Circumference, Cw	As Stated	$\pm$ 0.05 in.
		$\pm$ 1.3 mm

The method of partial derivatives is used to determine the inaccuracies in C_f. The derivative of C_f with respect to each parameter is evaluated at the desired speed, and multiplied by the uncertainty in the measurement of that parameter. The total error is then found by summing the individual errors.

Example: If a function F is dependent on a, b and c, i.e., F(a,b,c), then the error in F due to inaccuracies in a, b and c equals:

$$\delta F(a,b,c) = \left[\left(\frac{\partial F}{\partial a}\,\delta a\right)^2 + \left(\frac{\partial F}{\partial b}\,\delta b\right)^2 + \left(\frac{\partial F}{\partial c}\,\delta c\right)^2\right]^{\frac{1}{2}} \tag{6}$$

where δa, δb, δc are the inaccuracies in the measurements of a, b and c respectively and δF is the total inaccuracy in F.

Since $C_f = C_f\ (\Delta D_f/\Delta S,\ \rho,\ V,\ Cw)$ the error in C_f equals:

$$\delta C_f = \left[\left(\frac{\partial C_f}{\partial \frac{\Delta T}{\Delta S}}\ \delta \frac{\Delta D_f}{\Delta S}\right)^2 + \left(\frac{\partial C_f}{\partial \rho}\ \delta\rho\right)^2 + \left(\frac{\partial C_f}{\partial V}\ \delta V\right)^2 + \left(\frac{\partial C_f}{\partial Cw}\ \delta Cw\right)^2\right]^{1/2} \quad (7)$$

where $\dfrac{\Delta D_f}{\Delta S} = \dfrac{D_{f2} - D_{f1}}{S2 - S1}$ and S1 = 100 ft (30 m)

$D_{f2} = D_f$ at S1 = 100 ft (30 m)

S2 = 400 ft (120 m)

$D_{f2} = D_f$ at S2 = 400 ft (120 m).

An example of the procedure is given for a speed of 3 knots (1.5 m/s).

1. At 3 knots (1.5 m/s):

$$\frac{\partial C_f}{\partial \frac{\Delta D_f}{\Delta S}} = \frac{3.190}{Vk^2}$$

$$\frac{\partial C_f}{\partial \rho} = \frac{(1.647)(\Delta D_f/\Delta S)}{Vk^2}$$

$$\frac{\partial C_f}{\partial V} = \frac{-3.779\,\Delta D_f/\Delta S}{Vk^3}$$

$$\frac{\partial C_f}{\partial Cw} = \frac{-28.071\,\Delta D_f/\Delta S}{Vk^2}$$

$$\text{Error in } C_f = \left[\left(\frac{3.190}{9} \times 0.00118\right)^2 + \left(\frac{1.647 \times 0.0143}{9} \times 0.019\right)^2 + \left(\frac{-3.779 \times 0.0143}{27} \times 0.017\right)^2 + \left(\frac{28.071 \times 0.0143}{9} \times 0.004\right)^2\right]^{1/2}$$

$$= \left[(4.182 \times 10^{-4})^2 + (4.972 \times 10^{-5})^2 + (3.402 \times 10^{-5})^2 + (1.858 \times 10^{-4})^2\right]^{1/2}$$

$$= 0.000461.$$

2. Following the same procedure for a speed of 10 knots (5.1 m/s):

$$\text{Error in } C_f = \left[(5.933 \times 10^{-5})^2 + (4.664 \times 10^{-5})^2 + (9.574 \times 10^{-6})^2 + (1.743 \times 10^{-4})^2\right]^{\frac{1}{2}}$$

$$= 0.00019.$$

Therefore for Sample 1 in calm water, the floating length drag coefficients and inaccuracies are:

at 3 knots (1.5 m/s), $C_f = 5.03 \times 10^{-3} \pm 0.46 \times 10^{-3}$

at 10 knots (5.1 m/s), $C_f = 4.84 \times 10^{-3} \pm 0.19 \times 10^{-3}$.

The errors in the determination of C_f in wave conditions are assumed to be approximately equal to the errors in calm water.

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